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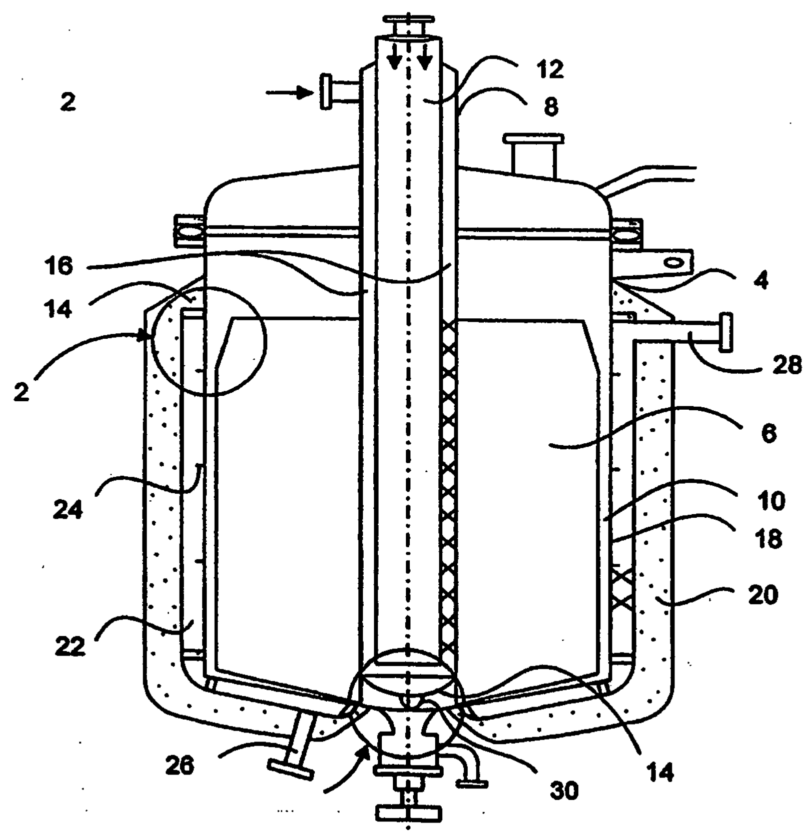
(57) Abstract

The present invention relates to a thermal transfer system for heating or cooling a medium. A structure (8, 37, 46, 50, 72, 81, 82, 89, 93, 98, 108, 306, 404) positioned inside a container (4, 34, 124, 302). The structure (8, 37, 46, 50, 72, 81, 82, 89, 93, 108, 306, 404) segments the container (4, 34, 124, 302) into a plurality of compartments (36, 95) wherein a distal end of the structure (8, 37, 46, 50, 72, 81, 82, 89, 93, 108, 306, 404) is in close proximity to an interior surface of the container (10, 33, 42, 91, 122, 210, 316, 414) to allow formation of a thermal transfer bridge (35, 208, 424, 426) that conducts heat into or out of the medium.



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Freezing and Thawing Vessel with Thermal Bridges

Cross-Reference to Related Applications

This application claims the benefit of Provisional Application Serial No. 60/037,283, filed February 4, 1997, hereby incorporated by reference. The present application is related to U.S. Patent Application Serial No. 08/895,782, (Attorney Docket No. 17882.705), filed July 17, 1997, entitled "Freezing and Thawing Vessel with Thermal Bridge Formed Between Container and Heat Exchange Member," having same named inventors Richard Wisniewski, Leonidas Cartwright Leonard, hereby incorporated by reference and U.S. Patent Application Serial No. 08/895,936, (Attorney Docket No. 17882.706), filed July 17, 1997, entitled "Freezing and Thawing Vessel with Thermal Bridge Formed Between Heat Exchange Members," having same named inventors Richard Wisniewski, Leonidas Cartwright Leonard, hereby incorporated by reference and U.S. Patent Application Serial No. 08/895,777, (Attorney Docket No. 17882.702), filed July 17, 1997, entitled "Freezing and Thawing Vessel with Thermal Bridge Formed Between Internal Structure and Heat Exchange Member," having same named inventors Richard Wisniewski, Leonidas Cartwright Leonard, hereby incorporated by reference.

1. Field of the Invention

The present invention relates generally to systems containing structures such as fins to aid in the transfer of heat into or out of a medium. More particularly, the present invention relates to heating and cooling structures which are suited for use in heat, cooling, thawing, and freezing biopharmaceutical products.

It is a yet another object of the present invention to have a system which encourages a controlled freezing process to promote dendritic ice growth to aid in the cryopreservation of mediums including but not limited to proteins, cells, blood, plasma, other biopharmaceutical products, or food products.

It is a further object of the present invention to have a system that can rapidly heat or cool a medium.

These and other objects of the present invention are achieved by the use of a structure positioned inside a container. The structure segments the container into a plurality of compartments wherein a distal end of the structure is in close proximity to an interior surface of the container to allow formation of a thermal transfer bridge that conducts heat into or out of the medium.

In one embodiment of the present invention, the structure includes a fin. A distal end of the fin is placed in close proximity to a portion of the container. Since the fin, and the container are not rigidly attached the structure, including the fin, can be removed from the container.

When a medium inside the container is frozen, a bridge made of the frozen medium will form between the distal end of the fin and the portion of the container close to the distal end of the fin. This bridge will allow heat to be conducted to or from the fin across the bridge speeding the removal of heat from the medium.

In one embodiment of the present invention, the fin is at least partially attached to a structure within the container allowing heat to be transferred out of the fin through the attachment point and the thermal bridge when it is formed.

In another embodiment of the present invention, the distal end of the fin is placed close enough to another surface of the container, for example, another fin or structure in the container, such that when the medium is cooled, the thermal transport bridge is formed between the fin and the other structure in the container -- which may of course be a fin.

In another embodiment of the invention a first heat exchange member is at least partially coupled to an interior surface of the container. A second heat exchange member at least partially coupled to the structure wherein a portion of

the first heat exchange member is placed in close proximity to a portion of the second heat exchange member to aid formation of a thermal transfer bridge that improves conduction of heat into or out of the medium. In one embodiment of the present invention, the structure and the second heat exchange member can be removed from the system to aid in cleaning since they are not rigidly attached to the container or the first heat exchange member.

Yet another embodiment of the invention comprises a heat exchange member which is at least partially coupled to an interior surface of the container wherein a distal end of the heat exchange member is placed in close proximity to the structure to allow formation of a thermal transfer bridge that conducts heat into or out of the medium. In another embodiment of the present invention, since the fin and the container are not rigidly attached the structure can be removed from the container.

The present invention is useful for both the cooling and heating of a medium. When a medium is being frozen the thermal bridges help transfer heat out of the medium. When the medium is being heated the thermal bridges help heat to be transferred into the medium.

The medium can also be a gas being converted to a liquid or a liquid being converted to a gas. In these cases the liquid phase of the medium that collects between the fin and the structure will act as the thermal bridge to enhance the conduction of heat between the fin and the structure.

Additionally, the fin can have structures on it which will enhance the formation of solid or liquid thermal bridges and/or enhance the heat conduction through such bridges. For example, a portion of the fin may be enlarged to provide more surface area for conduction and contact with a thermal bridge, or the fin may be tailored to enhance nucleation of the solid or condensation of the liquid. Also, a fin may have a non-uniform cross-section to enhance thermal transport or achieve desired thermal transport characteristics. This may be desirable to help achieve cryobiology protocols. Furthermore, the fin can have interior channels that allow a heat exchange medium to flow within at least a

portion of the fin. Other variations are possible without departing from the spirit of the invention.

The system may be configured so that a heating or cooling device is coupled to any portion of the container. For example, without departing from the present invention, a heater or cooler could be attached to an exterior portion of the container (e.g. a wall of the container), to an internal structure of the container, or directly to one or more of the fins.

In general, the system should be constructed such that the distance to be bridged by the thermal transport bridge will be a function of the thermal properties of the medium and the system, manufacturing requirements and construction processes used to build the system, and other relevant parameters of the system and components used. The size of the gap to be filled by the bridge can be determined through simple trial and error, and the optimum gap may be no gap.

In one aspect of the present invention, the fins may be structures of any shape which are placed against or wedged between surfaces in the container. Thermal bridges will then form between the fins and the adjacent surface or surfaces of the container. For example, the fins can have ends adapted to fit in preconfigured slots in surfaces of the container. In this way the fins can be reconfigurable attached to portions of the container so that the number, configuration, and type of the fins used can be easily changed to meet changing manufacturing, process, or protocol needs.

In one aspect of the present invention, the optimum gap is proportional to the thickness of the fin. In another aspect of the present invention, the optimum gap is less than 2 inches, preferably less than 1 inch, more preferably less than 1/2 inch, even more preferably less than 1/4 inch, and most preferably less than 1/8 inch.

Without departing from the present invention, the container can be porous and need not have a top or a bottom. The medium can be heated or cooled as it passes through the container. Additionally, the container used in the present invention is not limited in shape, size or material from which it is

constructed. In one aspect of the present invention, the container may have a volume of 1 liter to 5 liters, 1 liter to 250 liters, or 250 to 10,000 liters.

The present invention can be usefully applied in many fields. For example in the biopharmaceutical industry the present invention can be used to freeze and preserve a variety of biopharmaceutical products, including but not limited to proteins, cells, antibodies, medicines, plasma, blood, buffer solutions, viruses, serum, cell fragments, cellular components, and any other biopharmaceutical product.

Additionally, the present invention allows processing of such biopharmaceutical products consistent with generally accepted manufacturing procedures.

One could use the present invention to freeze a biopharmaceutical product by sterilizing the container, pumping the product to be frozen into the container through a sterile filter and then removing heat from the product using the present invention to freeze the product within the container.

The present invention promotes uniform freezing at a rapid pace which allows the product in the container to be frozen in as close to its native state as possible. Additionally, the present invention allows the freezing process to be done in a repeatable fashion so that a user can be assured that the freezing process is not causing batch to batch variations in the product. This allows the end use of the product to be decoupled from the manufacturing steps needed to create the product since the product can be stored in the frozen state after it is manufactured, and thawed when and where it is needed.

The present invention can also be used during any stage of a purification process. For example, after products are processed using size separation or affinity separation, fermentation, licing, concentration filtration, selective affinity chromatography, removal of micro contaminants or low level impurities through ion exchange, viral filtration, chromatography, putting the product in a buffered solution delivery system, or after any other processing step the resulting product can be stored using the present invention. This allows a hold

to be put on the manufacturing process without degrading the intermediate product.

For example, if during a manufacturing process in which various components are being separated, one wishes to put a hold on the processing, there may be contaminating proteases in the intermediate product which may, over time, degrade some of the proteins of interest in the product. The present invention can be used to freeze the intermediate product quickly and uniformly enough so that the product remains close to its native state. The molecules in the product are not brought significantly closer together--freeze concentration is reduced, and unwanted reactions can be slowed or stopped.

Thus, the present invention can be used to increase the flexibility of a manufacturing process, making planning and scheduling of the process easier. Intermediate products can be frozen for later processing or shipping. Additionally, since the present invention can be scaled to any size desired, large batches of products can be prepared all at once, preserved using the present invention, and used as needed at a later time.

BRIEF DESCRIPTION OF THE DRAWINGS

Figure 1 is a side view of the finned heating and cooling apparatus.

Figure 2 is a top view of the fins and the structure within the container depicted in Figure 1.

Figures 3a, 3b, and 3c depicts the formation of thermal bridges and graphs showing the temperature profile of various cross-sections of the container and medium.

Figure 3d depicts dendritic ice growth and the capture of units such as cells in the ice.

Figure 4 is another possible arrangement of the fins.

Figure 5 is yet another possible arrangement of the fins.

Figure 6 depicts a number of possible fin geometries and combinations.

Figure 7 depicts yet more possible fin geometries and combinations.

Figure 8 depicts still another possible configuration of fin geometries and combinations.

Figure 9 depicts a cross-sectional view of a fin showing a non-uniform thickness.

Figure 10 depicts a fins geometry which allows compartmentalization of the container through the use of alternate fin geometries.

Figure 11 is a cutaway view showing a container and the interior baffles of two fins.

Figure 12a is a top view of the container and fins of figure 11.

Figure 12b is a detail view of the distal end of a fin with an extension extending close to the interior wall of the container.

Figure 12c is a detail view showing another embodiment of a fin without an extension in which the hollow fins structure extends close to the interior wall of the container.

Figure 13 is a cutaway view showing a container, the interior baffles of two fins, and no central structure. The heat exchange fluid is fed into the fins through tubes in the top of the fins.

Figure 14a is a cutaway view showing a container, a set of interior fins, a set of exterior fins and a coil.

Figure 14b is a top view of the system of figure 14a.

Figure 15a is a cutaway view showing a container, a set of interior fins, a set of middle fins, a set of exterior fins, a first coil, and a second coil.

Figure 15b is a top view of the system of figure 15a.

Figure 15c is a detailed side view of the thermal bridges that form between each of the winds of the coils and between the fins and the winds of the coils.

Figure 15d is a detailed top view of the thermal bridges that form between the coils and the fins.

Figures 16a and 16b depict non-circular cross-section tubes.

Figures 17a and 17b depict non-circular cross-section tubes in use in a system.

Figures 18 depict non-circular cross-section tubes attached to fins in various configurations.

Figures 19a and 19b depict non-circular cross-section tubes in use in a coil configuration within a system.

Figure 20 depicts a configuration of non-circular cross-section tubes and fins useful for compartmentalizing a system.

DETAILED DESCRIPTION

One embodiment of the present invention is shown in Figure 1. Heating and cooling system 2 is comprised of container 4, fins 6 and structure 8. Fins 6 are configured such that they are placed in close proximity to interior surface 10 of container 4. Generally, a small gap between fin 6 and interior surface 10 is preferable. However, the size of this gap may be dictated by manufacturing tolerances, material parameters, or other practical considerations.

Figure 2 shows a cutaway top view of container 4, fins 6 and structure 8. In the present embodiment there are 6 fins placed symmetrically about structure 8. Any arrangement design, configuration, or number of fins could be used without departing from the present invention. For example, the fins need not be symmetrically positioned within the container, they need not be the same shape and they need not be made of the same material.

Referring again to Figure 1, structure 8 is heated or cooled by flowing a heat exchange fluid down interior passage 12 towards end piece 14. The heat exchange fluid then flows up through the outer passage 16 of structure 8. This flow pattern of the heat exchange fluid and the symmetric configuration of the fins about structure 8 aids system 2 to begin cooling the medium in the container from the bottom up. This is so because the heat exchange fluid is first closely coupled to the medium in the container and the fins at the bottom of the container.

Cooling the medium from the bottom up is particularly advantageous when a liquid medium is being frozen and, as is true for water, the density of the frozen medium is less than that if the liquid phase. Freezing from the bottom up prevents pressure from building up as might be the case if the liquid phase was constrained by the solid phase.

It should be appreciated that one skilled in the art could use other flow patterns, fin shapes, and fin configurations to induce the medium to heat or cool in any preferred direction, uniformly, and/or at a specified rate without departing from the present invention. Additionally, parameters of the heat exchange fluid such as flow rate and/or temperature can be used to affect the rate at which the medium is cooled.

End piece 14 has bottom fin 30 attached to it. Bottom fin 30 functions the same as fins 6. A thermal transport bridge is formed between bottom fin 30 and a portion of interior surface 10.

In one aspect of the present invention, taper 19 on fin 6 helps to slow the formation of a thermal bridge on the upper portion of fin 6. This will slightly slow the heat transfer out of the upper portion of the container, allowing the system to freeze the medium from the bottom up. Such a taper can be used on any portion of the fin to help create a preferred direction for removal of heat from the container.

Container 4 has jacket 20 surrounding its circumference. Between exterior surface 18 of container 4 and jacket 20 is fluid flow path 22. Spiral baffle 24 corkscrews around container 4 between exterior surface 18 and jacket 20 forcing heat exchange fluid in fluid flow path 22 to flow in a spiraling path around the exterior surface 18 of container 4. Heat exchange fluid flows into fluid flow path 22 through port 26 and out through port 28 resulting in the heat exchange fluid flowing around container 4 from the bottom to the top. This flow pattern for the heat exchange fluid aids system 2 in cooling the medium in the container from the bottom up.

It should be appreciated that other fluid flow patterns and baffles can be used to induce the medium to heat or cool in any preferred direction, uniformly, and/or at a specified rate without departing from the present invention. Additionally, parameters of the heat exchange fluid such as flow rate and/or temperature can be used to affect the rate at which the medium is cooled.

Furthermore, the heat exchange fluid can be flowed through the system at other points and in a time or process varying manner in order to tailor the

timing, direction, and rate of heat flow into or out of the system. Additionally, materials used in, or the shape, or configuration of the system, including the fins, can be used to control parameters of the heating or cooling process such as rate, timing or directionality.

When container 4, structure 8 and fins 6 are cooled by the coolant, the medium in the container begins to cool. When the medium is sufficiently cooled, a portion of the medium between the distal end of fins 6 and interior surface 10 will freeze. This frozen bridge will allow heat to be conducted between fins 6 and container 4 through the frozen bridge. This will enable heat to be taken out of the medium at a higher rate, speeding the freezing of the medium in the container. The present invention will work with any type of medium including but not limited to biopharmaceutical products.

Figure 3 illustrates the formation of thermal bridges in accordance with one aspect of the present invention. Figure 3a is a top view of one embodiment of the present invention in which structure 31 has 8 fins 32 attached to it. Each fin 32 extends close to interior surface 33 of container 34.

Figure 3b illustrates a simulation for the system shortly after thermal bridges 35 have begun to form. In this simulation, the material properties of 315 stainless steel were used for the container and the fins, and the coolant temperature was -45 °C. The temperature of the liquid was -0.2 °C, the temperature of the fin in contact with the liquid was close to -0.2 °C, and the temperature of the portion of the fin in contact with the frozen product was declining toward the temperature of the wall. The temperature of the wall was within 2-5 °C of the temperature of the coolant.

As can be seen from the graphs in figure 3b, heat is being extracted from fins 32 through both ends. When compared to a finned structure in which heat is extracted form only one end of the fin, the medium will be cooled at a faster rate. Figure 3c depicts the temperature profile of the medium within the compartments 36 formed by fins 32. As shown in the graphs in figure 3c, heat is withdrawn from the medium within the cavity through interior container wall 33, structure 31 and fins 32.

The relative uniformity with which the present invention allows heat to be removed from the medium promotes the growth of dendritic structures during the freezing process. The present invention, by allowing heat to be removed from both ends of a fin, helps to create a uniform temperature profile within the container. Additionally, the fins can be positioned to effectively segment the container into a plurality of smaller volumes, so that heat can be more uniformly removed from each segmented section. As an example, figure 2 shows container 4 segmented into 6 section by the fins.

It is noted that the present invention can be used to achieve dendritic ice growth even if fins are rigidly attached at more than one point to the system. Fins can be used to segment the container into small regions which can be more uniformly heated and cooled. Thus, if a particular application does not require that the internal structures of the container be removable, the fins and structures can be permanently attached within the container.

Dendritic ice growth is particularly useful many areas, including but not limited to the cryopreservation of biopharmaceutical products. As shown in Figure 3d, when heat is removed from surface 501 (which could be any surface of the present invention), dendrites 502 will form and grow moving away form surface 501. As dendrites 502 grow, the substance 503 in the medium being frozen and will eventually become surrounded by dendrites 502. As dendrites 502 grow, substance 503 will eventually become trapped in the frozen medium 504. By controlling the heat removal from surface 501, the growth rate of dendrites 502 can be controlled. Controlling the growth rate of dendrites 502 allows the present invention to be used to control the amount of liquid removed from substance 503 as it enters and becomes trapped by growing dendritic front 505. It is noted that substance 503 can be any substance one desires to preserve.

It should be appreciated that there need not be active cooling of both the structure and the container to employ the present invention. Without departing from the present invention, coolant can be circulated through any part of the system, only one part of the system, or coolant need not be used and the system could be cooled by other means or indirectly or passively.

In another embodiment of the invention, removable liners can be placed over the distal ends of fins 6 to prevent them from contacting interior surface 10 when structure 8 and fins 6 are inserted or removed from container 4. This may be desired, for example, to avoid scratching interior surface 10 with fins 6 during assembly and disassembly.

Other fin configuration are possible without deviating from the present invention. For example, in Figure 4, fins 39 may be partially coupled to interior container wall 41 and the distal end of each fin can be place in close proximity to structure 37 such that the thermal bridge is formed between a distal end of each of fins 39 and structure 37.

In Figure 5, fins 40 are attached to interior surface 42. Fins 44 are attached to structure 46. System 38 is constructed such that portions of fins 40 and fins 44 are in contact, nearly in contact or can be rotated such that this is the case. Then, when the medium in the container freezes, thermal transport bridges will form between portions of fins 40 and fins 44. In another aspect of this invention, fins 40 and 44 need not be parallel. Fins 40 and 44 can be angled with respect to each other such that gap 45 varies along the length of fins 40 and 44.

Figure 6 depicts a number of possible arrangements of fins. For example, fin 48A may be partially coupled to structure 50A and a distal end placed in close proximity to another structure, 50B, such that the thermal bridge is formed between the distal end of fin 48A and structure 50B Fins 54 are coupled to interior wall 56. A distal end of fin 54A is placed near distal ends of fins 58, and fins 58 are coupled to structures 50. A thermal bridge will form between the distal ends of fins 54A, 58A and 58B. Thus, a thermal bridge can be formed between more than two fins. Forming a thermal bridge between two or more fins may be desirable if, for example, design constraints or other constraints require portions of the container to be held a distance from an actively cooled surface. A fin and thermal bridge can be used to help extract heat from the isolated structure.

Figure 7 depicts a number of other possible arrangements of fins. A fin can be configured so that the thermal bridge is formed not between the distal ends of two fins but between the distal end of one fin and some other portion of another fin. For example, fin 60 will form a thermal bridge with fin 62 at a central portion of fin 60, and fin 64 will form a thermal bridge with fin 66 at a central portion of fin 64. Furthermore, a fin need not be initially coupled to anything and thermal transport bridges may be formed between portions of the fin and other portion of the system. For example, fin 68 is not rigidly attached to any structure within the container, but it will form a thermal bridge with fins 64 and 70 and structures 72.

Additionally, fins may have structures on them to aid in the formation of thermal transport bridges or to enhance the thermal transport capabilities of the bridges. Fins 62 have extended surfaces 76 on their distal ends. Extended surface 76 will allow a wider thermal bridge to be formed, improving the heat transfer rate of the bridge. This may be desirable in certain circumstances. For example, the thermal transport properties of the fin material may be superior to those of the frozen material that forms the thermal bridge. Increasing the area of the thermal bridge will improve its total heat transfer properties.

Additionally, other types of extended surfaces can be put on fins, the structures or the interior surface of the container to aid in the formation of thermal transport bridges with the desired properties. For example, extended surface 78 may be used to enhance the formation of a thermal bridge with fin 62 whether or not extended surface 76 is attached to fin 62.

Figure 8 shows another embodiment of the present invention. This embodiment details another configuration of fins in accordance with the present invention. In this embodiment fins 80 are connected to structure 81 and will form thermal bridges with structures 82. Fins 83 are connected to structures 82 and will form thermal bridges with interior container wall 84. Fins 85 will form thermal bridges with each other, and fins 86 will form thermal bridges with interior container wall 84

Figure 9 shows yet another embodiment of the present invention. Fin 87 has a non-uniform cross section along its length. Fin 87 is thicker at end 88 where it connects to structure 89 and thinner in its central portion. The fin then widens out at its distal end 90 where it is in close proximity to interior surface 91 A thermal bridge will form between distal end 90 and interior surface 91. The thicker base of the fin will allow more heat flux to be withdrawn from the fin at end 88 and distal end 90.

Figure 10 shows still another embodiment of the present invention. Fins 92 are attached to structure 93 and will form thermal bridges with container wall 94. Fins 92 are curved to form compartments 95. Compartmentalization of the container allows more uniform cooling to be achieved since the distance from any point in the medium to a cooled surface is reduced. Also, the reduction in distance between cooled surfaces can be used to decrease the time required to freeze a medium. Other fins such as fins 96 may be added to further compartmentalize compartments 95. Fins 97 can also be used to form thermal bridges with another structure 98. Those skilled in the art will realize that other shapes and configurations of fins can be used to create more or less compartments of any desired size, and that this scheme can be scaled to any desired container volume without departing from the present invention.

Figure 11 shows another embodiment of the present invention. In this embodiment fins 102 have interior passageways 104. Heat exchange fluid flows into interior passageways 104 through openings 106 in structure 108. Fins 102 may have dimples 110 or spacers 114 or turbulizers to help optimize the flow pattern 118 of the heat exchange fluid. Dimples or spacers help optimize the flow pattern 118 of the heat exchange fluid for reasons including, increasing the interior surface area of the fin which comes in contact with the heat exchange fluid, and giving the heat exchange fluid more time to absorb heat from the fins. This speeds the freezing process and allows converging of the dendrites more quickly.

In another aspect of the present invention, fins 102 may have extensions 120 on them. As shown in Figure 12a, heat exchange fluid does not flow within

extensions 120. Extensions 120 are connected to fins 102 and extend close to interior surface 122 of container 124. Figure 12b shows a detail view of fin 102, extension 120 and interior surface 122. Figure 12c shows a detail view of another embodiment of the present invention in which there is no extension placed on the end of fin 102.

As show in figure 12b, when the present invention is used to freeze a medium within container 124, a thermal transfer bridge 126 will begin to form between interior surface 122 and extension 120. In figure 12c, the thermal transfer bridge will begin to form between fin 102 and interior surface 122.

Figure 13 shows yet another embodiment of the present invention. In this embodiment the heat exchange fluid flows into and out of fins 202 through tubes 204 connected to the top 206 of fins 202. In this embodiment the fins are not connected to a central structure. When this embodiment is used to freeze a medium, thermal transfer bridges 208 will form between the fins 202 and the interior surface 210 and between interior portions 212 of fins 202.

Figure 14a depicts yet another embodiment of the present invention. In this embodiment, system 300 has internal fins 304 which are attached to structure 306. Heat exchange fluid flows through structure 306. The flow of the heat exchange fluid can be configured to be similar to the flow described for structure 8 in figure 1. Any other flow configuration can be used to achieve a desired cooling or heating rate. Additionally, heat exchange fluid may be flowed through interior fins 304 if desired.

Coil 308 is placed in a surrounding relationship to interior fins 304. Heat exchange fluid flows into coil 308 through input 310 and flows out through output 312. Exterior fins 314 are placed between coil 308 and interior surface 316 of container 302. In one aspect of this embodiment, exterior fins can be free standing, attached to coil 308 or attached to interior surface 316. In another aspect of this embodiment, heat exchange fluid can be flowed through exterior fins 314 through coil 308, interior surface 316, external inputs, or any other supply.

In this embodiment, thermal transport bridges are formed between interior fins 304 and coil 308, coil 308 and external fins 314, external fins 314 and interior surface 316, and the coils of coil 308.

Figure 14b show a top view of system 300. In this embodiment fins 314 are depicted as not being attached to coil 308. Fins 314 could be suspended by supports from the top or bottom of container 302 or fins 314 could be free standing.

Figure 15 depicts still another embodiment of the present invention. In this embodiment system 400 has internal fins 402 attached to structure 404 and first coil 406 surrounding internal fins 402. Middle fins 408 are placed around first coil 406 and second coil 410 surrounds middle fins 408. Exterior fins 412 are placed between second coil 410 and interior surface 414. First and second coils 406 and 410 receive heat exchange fluid through input 416 and 418 respectively and the heat exchange fluid flows out through outputs 420 and 422 respectively.

Figure 15b shows a top view of this embodiment. In this embodiment fins 408 and 412 are depicted as freely suspended. Thermal transport bridges will form between internal fins 402 and first coil 406, the coils of first coil 406, first coil 406 and middle fins 408, middle fins 408 and second coil 410, the coils of second coil 410, second coil 410 and exterior fins 412, and exterior fins 412 and interior surface 414.

Figure 15c shows a detail side view of the formation of the thermal transport bridges 424 between the coils of one of first coil 406 or second coil 410, and the thermal transport bridges 426 formed between the coils and fins, interior fins middle fins or exterior fins. Distances X1 and X2 can be optimized as desired as a function of the properties of the fins the coil the medium and the container. The Figure 15d shows a top view of the formation of the thermal bridges depicted in figure 15c.

Figures 16 show other possible configurations of coils consistent with the present invention. In Figure 16a, central pipe 602 has a round cross section. Cooling fluid flows through the interior of pipe 602. Central pipe 602 is

adjacent to and will form a thermal bridge with fin 604. Pipe 606 also has cooling fluid flowing through it, and it is adjacent to the other end of fin 604. Pipe 606 has a non-circular cross-section. Any cross-section pipe can be used consistent with the present invention. In figure 16b, a non-circular cross-section pipe 608 is show in a different orientation with respect to the adjacent fins.

Figure 17 shows non-circular cross-section pipes used in a system. In figure 17a, the angle formed between two adjacent fins is small and therefore the non-circular cross section pipes 610 are oriented so that they can be placed closer together. One advantage of using non-circular cross-section pipes is that the elongated surface area of non-circular pipes 610 allows for a longer portion of the interface between compartments 612 to be cooled by a pipe with a cooling medium flowing through it.

Figure 17b shows non-circular cross-section pipe 614 used in a different orientation from that in Figure 17a. In Figure 17b, the angle formed by adjacent fins is larger and therefore non-circular cross-section pipes 614 can be used in the orientation shown. In the orientation shown, non-circular cross-section pipes 614 protrude into the adjacent compartments and advantageously help to more uniformly cool the medium within the compartments.

Figure 18 shows another configuration of pipes and fins that is consistent with the present invention. In figure 18, the non-circular cross-section pipes 702 have fins 704 welded onto them.

Figures 19 show yet another example of the use of non-circular cross-section fins consistent with the present invention. In figure 19a a non-circular cross-section pipe 802 is wound into a coil, similar to coil 308 of figure 14a. Non-circular cross-section pipe 802 has extended flat side 804 adjacent to fins 806. Extended flat side 804 makes it easier for thermal bridges to form between coil 808 formed by pipes 802 and fins 806, and between pipes 802 of coil 808. Figure 19b shows pipes 810 of a different cross-section which also advantageously aid in the formation of thermal bridges.

Non-circular cross-section pipes 802 or 810 allow fins 806 or fins 812 to be closer together for a given internal pipe cross-sectional area when compared

to a circular pipe. Since the fins are closer together, thermal bridges will form more quickly, speeding up the freezing process and keeping it more uniform.

Figure 20 details yet another possible configuration of non-circular cross-section pipes 902 and fins 904. The geometry shown can be used to compartmentalize large volume tanks. The compartments thus formed can be made as small as is needed in order to achieve a desired level of uniformity.

The present invention can be usefully applied in many fields. For example in the biopharmaceutical industry the present invention can be used to freeze and preserve a variety of biopharmaceutical products, including but not limited to proteins, cells, antibodies, medicines, plasma, blood, buffer solutions, viruses, serum, cell fragments, cellular components, and any other biopharmaceutical product.

Additionally, the present invention allows processing of such biopharmaceutical products consistent with generally accepted manufacturing procedures.

One could use the present invention to freeze a biopharmaceutical product by sterilizing the container, pumping the product to be frozen into the container through a sterile filter and then removing heat from the product using the present invention to freeze the product within the container.

The present invention promotes uniform freezing at a rapid pace which allows the product in the container to be frozen in as close to its native state as possible. Additionally, the present invention allows the freezing process to be done in a repeatable fashion so that a user can be assured that the freezing process is not causing batch to batch variations in the product. This allows the end use of the product to be decoupled from the manufacturing steps needed to create the product since the product can be stored in the frozen state after it is manufactured, and thawed when and where it is needed.

The present invention can also be used during any stage of a purification process. For example, after products are processed using size separation or affinity separation, fermentation, licing, concentration filtration, selective affinity chromatography, removal of micro contaminants or low level impurities

through ion exchange, viral filtration, chromatography, putting the product in a buffered solution delivery system, or after any other processing step the resulting product can be stored using the present invention. This allows a hold to be put on the manufacturing process without degrading the intermediate product.

For example, if during a manufacturing process in which various components are being separated, one wishes to put a hold on the processing, there may be contaminating proteases in the intermediate product which may, over time, degrade some of the proteins of interest in the product. The present invention can be used to freeze the intermediate product quickly and uniformly enough so that the product remains close to its native state. The molecules in the product are not brought significantly closer together--freeze concentration is reduced, and unwanted reactions can be slowed or stopped.

These examples do not limit the present invention but are merely examples of possible embodiments of the present invention. Other embodiments are possible without deviating form the present invention.

WHAT IS CLAIMED IS:

1. A thermal transfer system, comprising:

a container for receiving a medium;

a structure positioned in the container such that the structure segments the container into a plurality of compartments wherein a distal end of the structure is in close proximity to an interior surface of the container to allow formation of a thermal transfer bridge that conducts heat into or out of the medium.

2. A thermal transfer system as in claim 1 including:

a heating or cooling device coupled to and provides heating or cooling of the container.

3. A thermal transfer system as in claim 1 including:

a heating or cooling device coupled to and provides heating or cooling of the structure.

4. A thermal transfer system as in claim 1 including:

a heating or cooling device coupled to and provides heating or cooling of the container and the structure.

5. A thermal transfer system as in claim 1 including:

a plurality of structures in the container.

6. A thermal transfer system as in claim 1, including:

a removable liner configured to cover at least a portion of the structure.

7. A thermal transfer system as in claim 1 wherein:

a volume of the container is in the range from substantially 1 liter to 250 liters.

8. A thermal transfer system as in claim 1 wherein:

a volume of the container is in the range from substantially 250 liter to 10,000 liters.

9. A thermal transfer system as in claim 1 wherein:

a distance between the distal end of the structure and the interior surface of the container is a non-contacting distance not greater than one inch.

10. A thermal transfer system as in claim 1 wherein:

the container includes a jacket defining an interstitial space positioned between the jacket and a wall of the container for receiving a flow of a heat exchange fluid, the jacket further including a plurality of spiral baffles for enhancing thermal exchange between the heat exchange fluid and the container.

11. A thermal transfer system as in claim 1 wherein:

a heat exchange fluid flows within the structure.

12. A thermal transfer system as in claim 11 wherein:

an interior portion of the structure has baffles.

13. A thermal transfer system as in claim 12 wherein:

the structure is configured to maximize an area of a surface of the structure that is in contact with the medium.

14. A thermal transfer system as in claim 1 wherein:

the medium is heated or cooled such that a thermal gradient is created in a predetermined direction.

15. A thermal transfer system as in claim 1 wherein:

the medium is heated or cooled such that a thermal gradient is created in a predetermined direction and the heating or cooling occurs at a predetermined rate.

16. A thermal transfer system as in claim 1 wherein:
the medium is a biopharmaceutical product.

17. A thermal transfer system as in claim 1 wherein:
the medium includes proteins.

18. A thermal transfer system comprising:
a container for receiving a medium;
a structure positioned in the container, a heat exchange member at least partially coupled to the structure and extending into the container wherein a distal end of the heat exchange member is placed in close proximity to an interior surface of the container to allow the formation of a thermal transfer bridge that conducts heat into and out of the medium.

19. A thermal transfer system as in claim 18 wherein:
a heating or cooling device is coupled to and provides heating or cooling of the container.

20. A thermal transfer system as in claim 18 wherein:
a heating or cooling device is coupled to and provides heating or cooling of the structure positioned inside the container.

21. A thermal transfer system as in claim 18 wherein:
a heating or cooling device is coupled to and provides heating or cooling of the structure and the container.

22. A thermal transfer system as in claim 18 wherein:

there is a plurality of heat exchange members.

23. A thermal transfer system as in claim 18, further comprising: a removable liner configured to cover at least a portion of the heat exchange member.

24. A thermal transfer system as in claim 18 wherein: a volume of the container is in the range from substantially 1 liter to 250 liters.

25. A thermal transfer system as in claim 18 wherein: a volume of the container is in the range from substantially 250 liter to 10,000 liters.

26. A thermal transfer system as in claim 18 wherein: the container includes a jacket defining an interstitial space positioned between the jacket and a wall of the container for receiving a flow of a heat exchange fluid, the jacket further including a plurality of spiral baffles for enhancing thermal exchange between the heat exchange fluid and the container.

27. A thermal transfer system as in claim 18 wherein: a heat exchange fluid flows within the structure.

28. A thermal transfer system as in claim 18 wherein: the heat exchange fluid flows into the structure through an interior passage in the structure.

29. A thermal transfer system as in claim 18 wherein: the heat exchange fluid flows out of the structure through an outer passage in the structure wherein one portion of the outer passage comprises an outer wall of the structure.

30. A thermal transfer system as in claim 18 wherein:
a heat exchange fluid flows within the heat exchange member.

31. A thermal transfer system as in claim 27 wherein:
an interior portion of the structure has baffles.

32. A thermal transfer system as in claim 30 wherein:
an interior portion of the heat exchange member has baffles.

33. A thermal transfer system as in claim 27 wherein:
an interior portion of the portion of the structure extending into the container has baffles.

34. A thermal transfer system as in claim 27 wherein:
the heat exchange fluid flows into the heat exchange member from the structure.

35. A thermal transfer system as in claim 18 wherein:
a heat exchange fluid flows into the heat exchange member from a heat exchange supply line.

36. A thermal transfer system as in claim 26 wherein:
the heat exchange fluid flows does not flow through the distal end of the heat exchange member.

37. A thermal transfer system as in claim 18 wherein:
a distance between the distal end of the heat exchange member and the interior surface of the container is a non-contacting distance not greater than one inch.

38. A thermal transfer system as in claim 18 wherein:

the medium is heated or cooled such that a thermal gradient is created in the medium in a predetermined direction

39. A thermal transfer system as in claim 18 wherein:

the medium is heated or cooled such that a thermal gradient is created in a predetermined direction and the heating or cooling occurs at a predetermined rate.

40. A thermal transfer system as in claim 18 wherein:

the medium is a biopharmaceutical product.

41. A thermal transfer system as in claim 18 wherein:

the medium includes proteins.

42. A thermal transfer system comprising:

a container for receiving a medium;

a structure positioned in the container;

a heat exchange member at least partially coupled to an interior surface of the container wherein a distal end of the heat exchange member is placed in close proximity to the structure to allow formation of a thermal transfer bridge that conducts heat into or out of the medium.

43. A thermal transfer system as in claim 42 including:

a heating or cooling device coupled to and provides heating or cooling of the container.

44. A thermal transfer system as in claim 42 including:

a heating or cooling device coupled to and provides heating or cooling of the structure.

45. A thermal transfer system as in claim 42 including:

a heating or cooling device coupled to and provides heating or cooling of the heat exchange member.

46. A thermal transfer system as in claim 42 including:

a heating or cooling device coupled to and provides heating or cooling of the container and the structure.

47. A thermal transfer system as in claim 42, including:

a plurality of heat exchange members.

48. A thermal transfer system as in claim 42, including:

a removable liner configured to cover at least a portion of the heat exchange member.

49. A thermal transfer system as in claim 42, including:

a removable liner configured to cover at least a portion of the structure.

50. A thermal transfer system as in claim 42 wherein:

a volume of the container is in the range from substantially 1 liter to 250 liters.

51. A thermal transfer system as in claim 42 wherein:

a volume of the container is in the range from substantially 250 liter to 10,000 liters.

52. A thermal transfer system as in claim 42 wherein:

a distance between the distal end of the heat exchange member and the structure is a non-contacting distance not greater than one inch.

53. A thermal transfer system as in claim 42 wherein:

the container includes a jacket defining an interstitial space positioned between the jacket and a wall of the container for receiving a flow of a heat exchange fluid, the jacket further including a plurality of spiral baffles for enhancing thermal exchange between the heat exchange fluid and the container.

54. A thermal transfer system as in claim 42 wherein:
a heat exchange fluid flows within the structure.

55. A thermal transfer system as in claim 42 wherein:
a heat exchange fluid flows within the heat exchange member.

56. A thermal transfer system as in claim 42 wherein:
an interior portion of the heat exchange member has baffles.

57. A thermal transfer system as in claim 42 wherein:
the heat exchange member is configured to maximize an area of a surface of the heat exchange member that is in contact with the medium.

58. A thermal transfer system as in claim 42 wherein:
the medium is heated or cooled such that a thermal gradient is created in a predetermined direction.

59. A thermal transfer system as in claim 42 wherein:
the medium is heated or cooled such that a thermal gradient is created in a predetermined direction and the heating or cooling occurs at a predetermined rate.

60. A thermal transfer system as in claim 42 wherein:
the medium is a biopharmaceutical product.

61. A thermal transfer system as in claim 42 wherein:

the heat exchange member is at least partially coupled a bottom of the container.

62. A thermal transfer system as in claim 42 wherein:
the medium includes proteins.

63. A thermal transfer system comprising:
a container for receiving a medium;
a structure positioned in said container;
a first heat exchange member at least partially coupled to an interior surface of said container;
a second heat exchange member at least partially coupled to said structure wherein a portion of said first heat exchange member is placed in close proximity to a portion of said second heat exchange member to aid formation of a thermal transfer bridge that improves conduction of heat into or out of the medium.

64. A thermal transfer system as in claim 63 wherein:
a heating or cooling device is coupled to and provides heating or cooling of said container.

65. A thermal transfer system as in claim 63 wherein:
a heating or cooling device is coupled to and provides heating or cooling of said structure positioned inside said container.

66. A thermal transfer system as in claim 63 wherein:
a heating or cooling device is coupled to and provides heating or cooling of said structure and said container.

67. A thermal transfer system as in claim 63 wherein:
there is a plurality of heat exchange members.

68. A thermal transfer system as in claim 63, further comprising:

a removable liner configured to cover at least a portion of said first heat exchange member.

69. A thermal transfer system as in claim 63, further comprising:

a removable liner configured to cover at least a portion of said second heat exchange member.

70. A thermal transfer system as in claim 63, further comprising:

a removable liner configured to cover at least a portion of said first heat exchange member and said second heat exchange member.

71. A thermal transfer system as in claim 63 wherein:

a volume of said container is in the range from substantially 1 liter to 250 liters.

72. A thermal transfer system as in claim 63 wherein:

a volume of said container is in the range from substantially 250 liter to 10,000 liters.

73. A thermal transfer system as in claim 63 wherein:

a distance between said distal end of said first heat exchange member and a distal end of said second heat exchange member is a non-contacting distance not greater than one inch.

74. A thermal transfer system as in claim 63 wherein:

the container comprises a jacket defining an interstitial space positioned between the jacket and a wall of the container for receiving a flow of a cooling fluid said jacket further including a plurality of spiral baffles for enhancing thermal exchange between said fluid and said container.

75. A thermal transfer system as in claim 63 wherein:

said medium is heated or cooled such that a thermal gradient is created in a predetermined direction.

76. A thermal transfer system as in claim 63 wherein:

said medium is heated or cooled such that a thermal gradient is created in a predetermined direction and said heating or cooling occurs at a predetermined rate.

77. A thermal transfer system as in claim 63 wherein:

said medium is a biopharmaceutical product.

78. A thermal transfer system as in claim 63 wherein:

said second heat exchange member is placed at an end of said structure.

79. A thermal transfer system as in claim 63 wherein:

a heat exchange fluid flows within the structure.

80. A thermal transfer system as in claim 63 wherein:

a heat exchange fluid flows within the first heat exchange member.

81. A thermal transfer system as in claim 63 wherein:

an interior portion of the first heat exchange member has baffles.

82. A thermal transfer system as in claim 63 wherein:

the first heat exchange member is configured to maximize an area of a surface of the heat exchange member that is in contact with the medium.

83. A thermal transfer system as in claim 63 wherein:

a heat exchange extension is at least partially coupled to the first heat exchange member.

84. A thermal transfer system as in claim 63 wherein: the medium includes proteins.

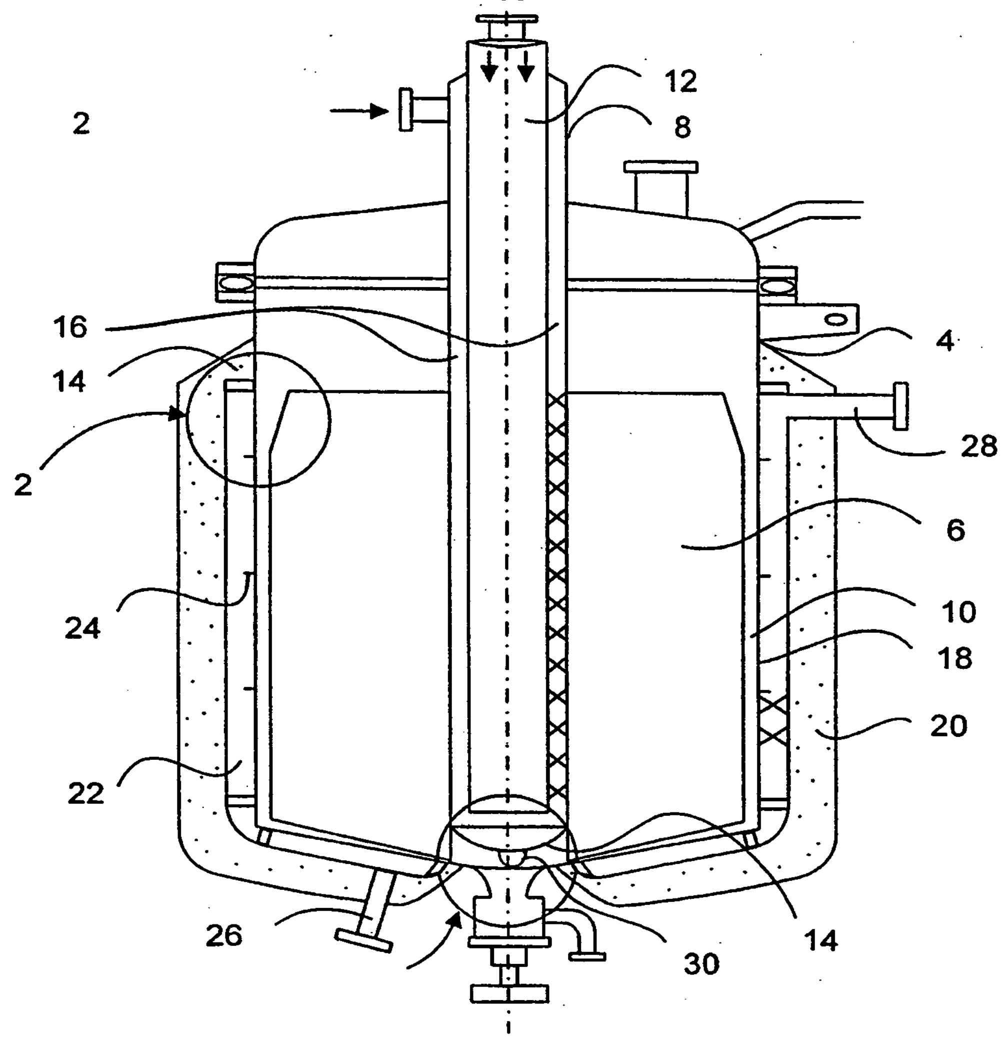

FIG. 1

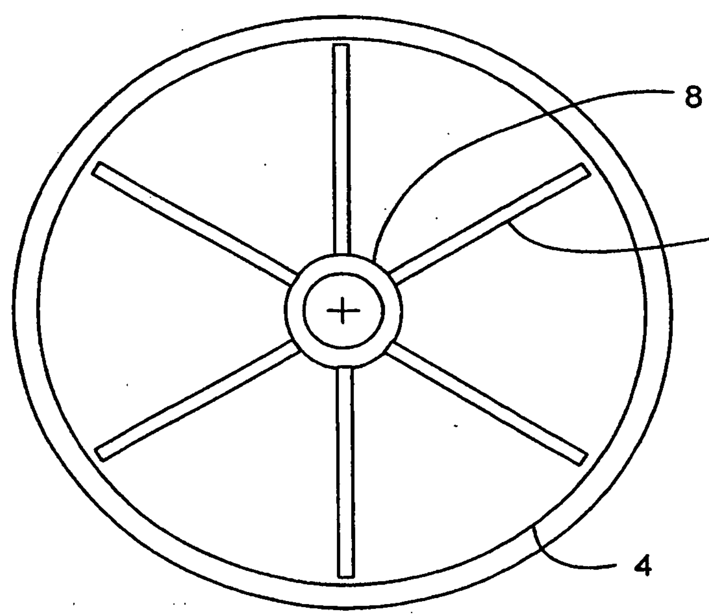

FIG. 2

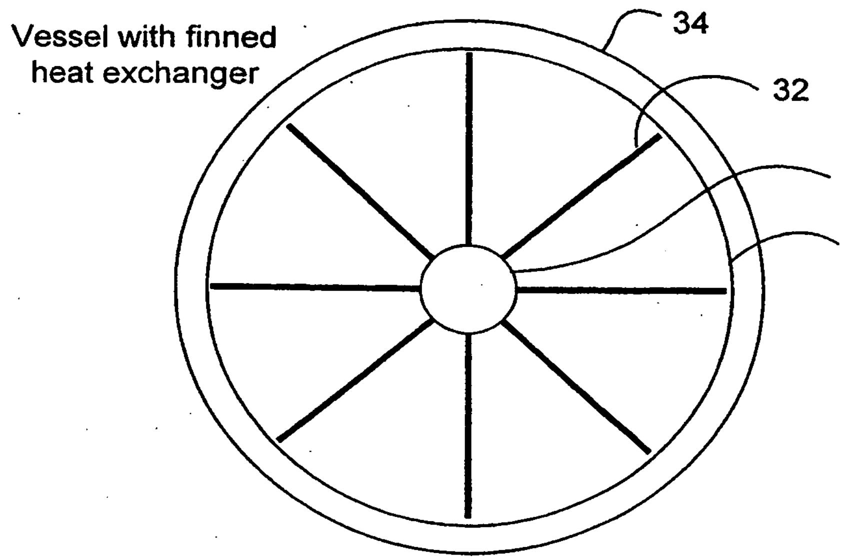
Vessel with finned heat exchanger
34
32
31
33

FIG. 3a

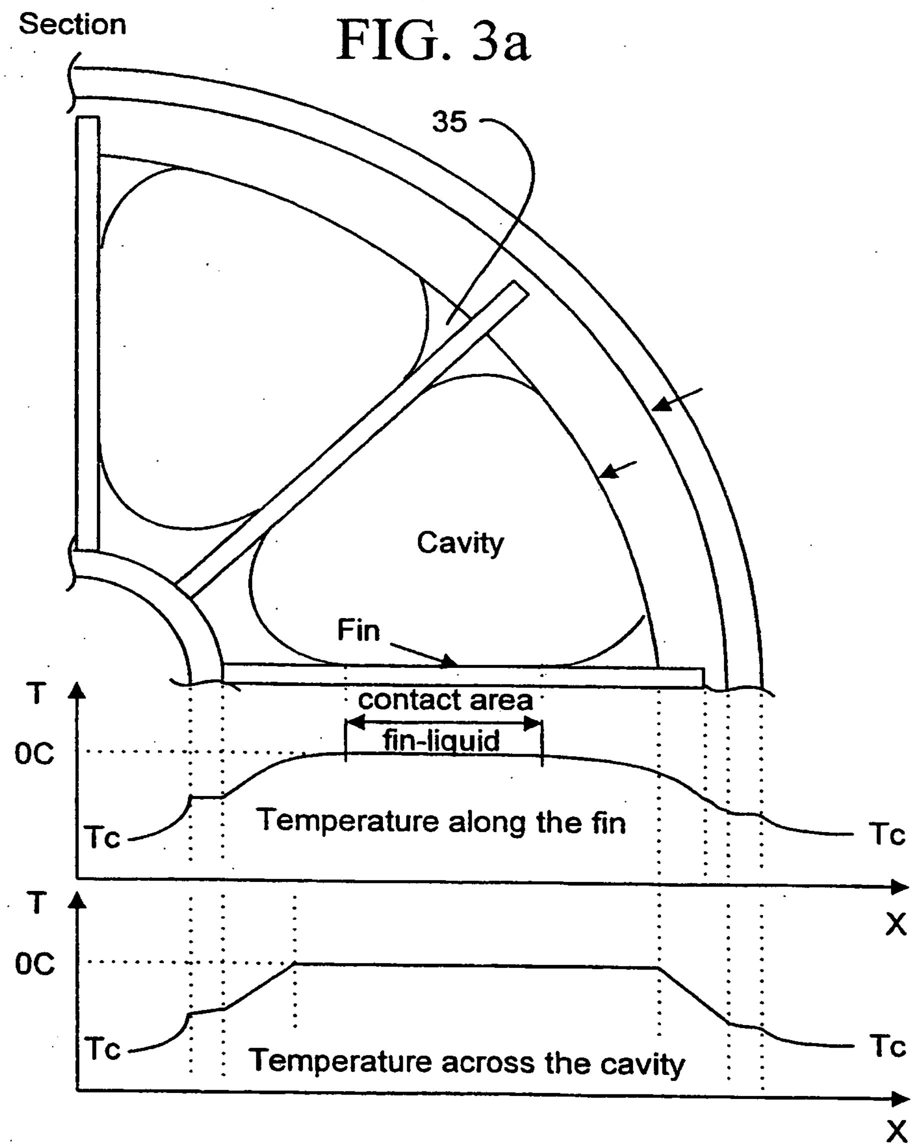
Section
35
Cavity
Fin
contact area
fin-liquid
T
0C
Tc
Temperature along the fin
Tc
X
T
0C
Tc
Temperature across the cavity
Tc
X

FIG. 3b

Section of the vessel with internal finned Heat exchanger

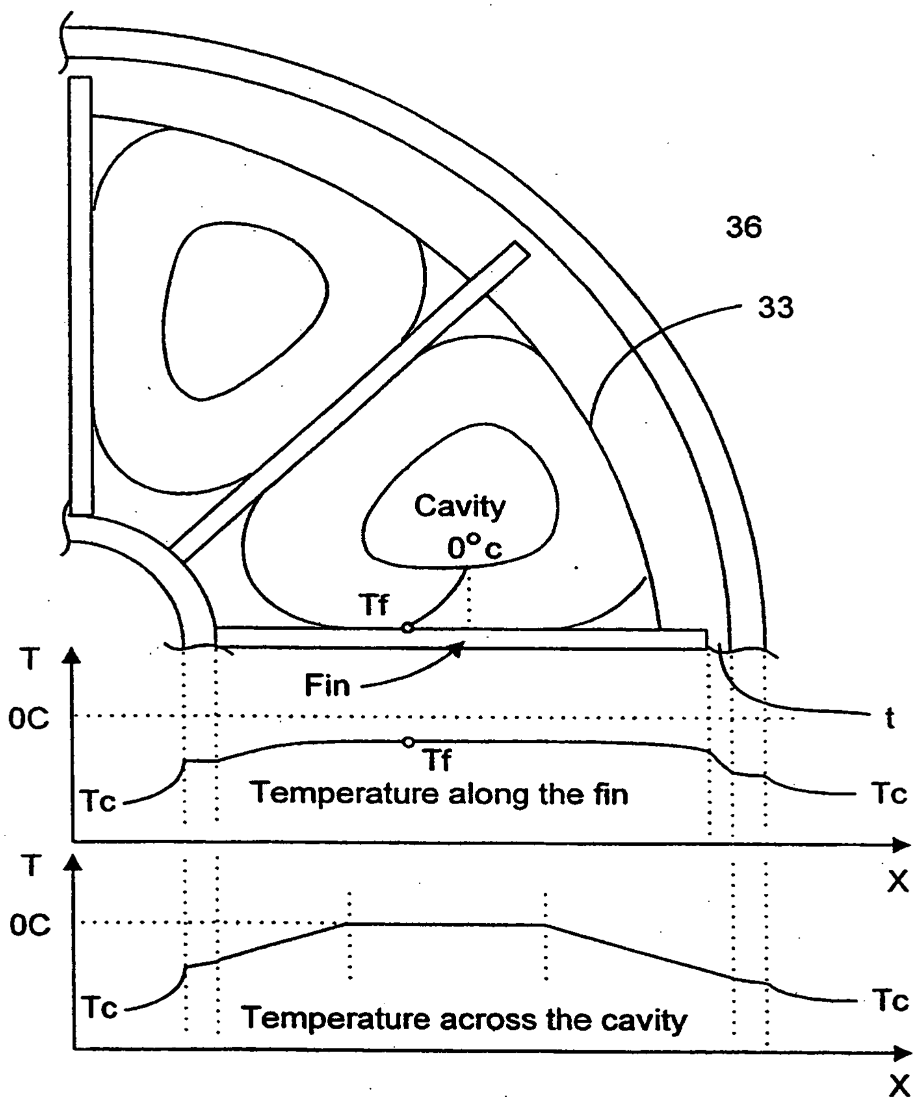

FIG. 3c

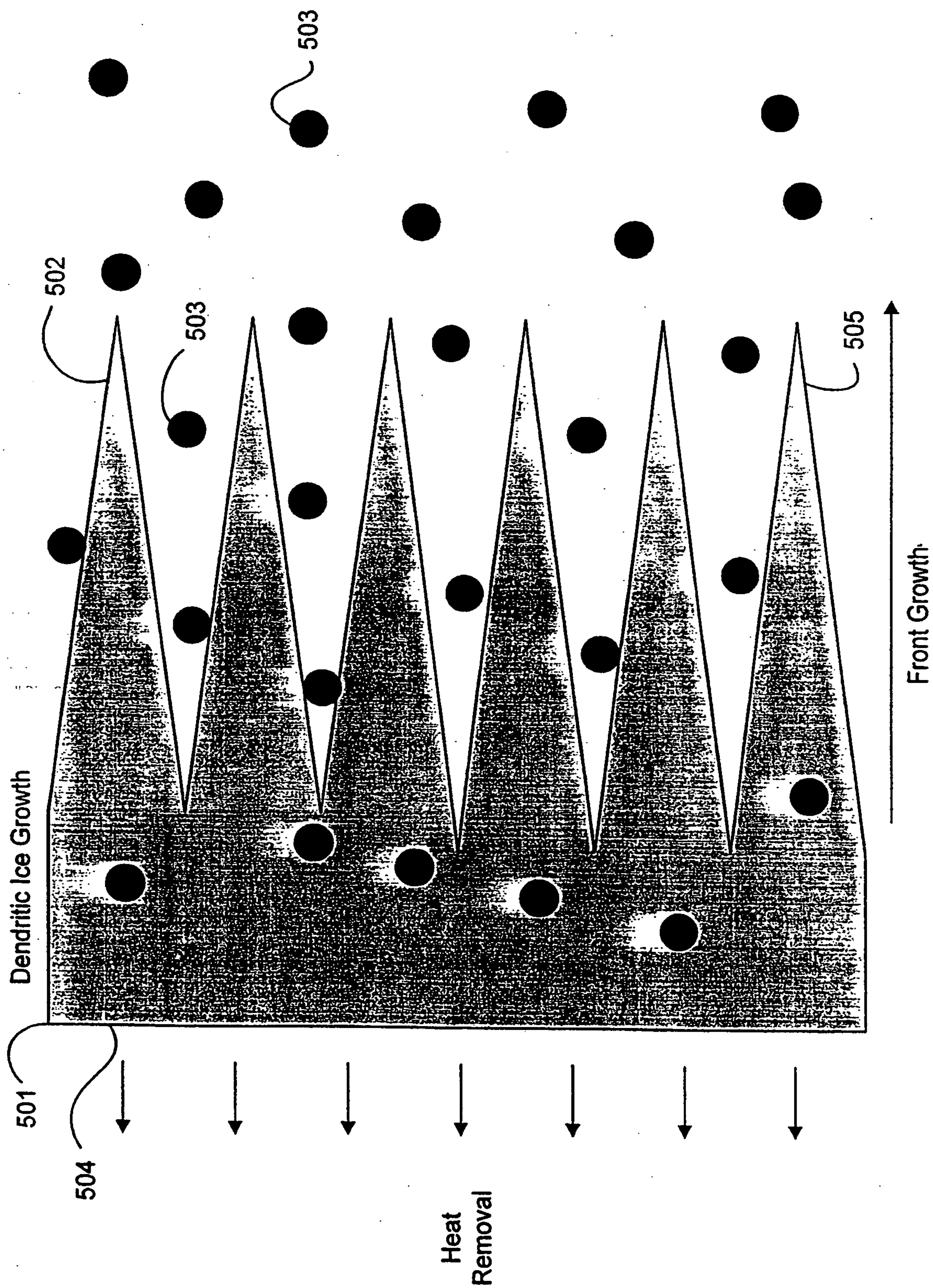
503
502
503
505
Dendritic Ice Growth
Front Growth
501
504
Heat
Removal

FIG. 3d

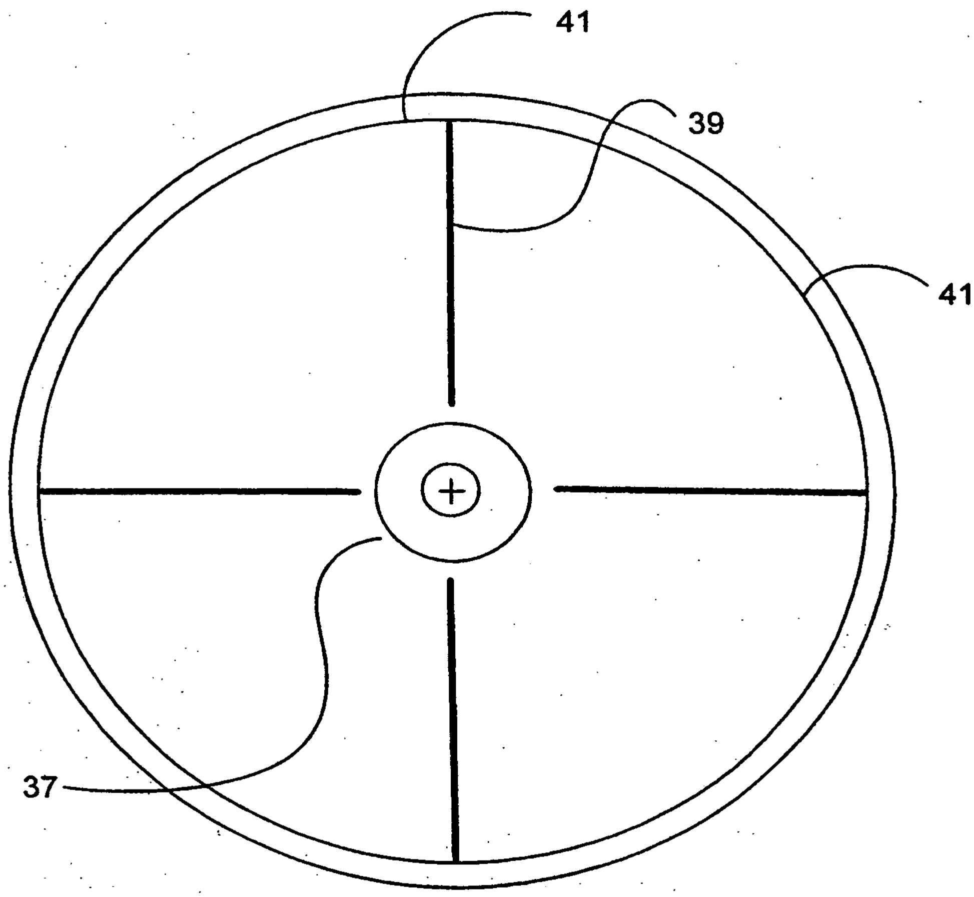

FIG. 4

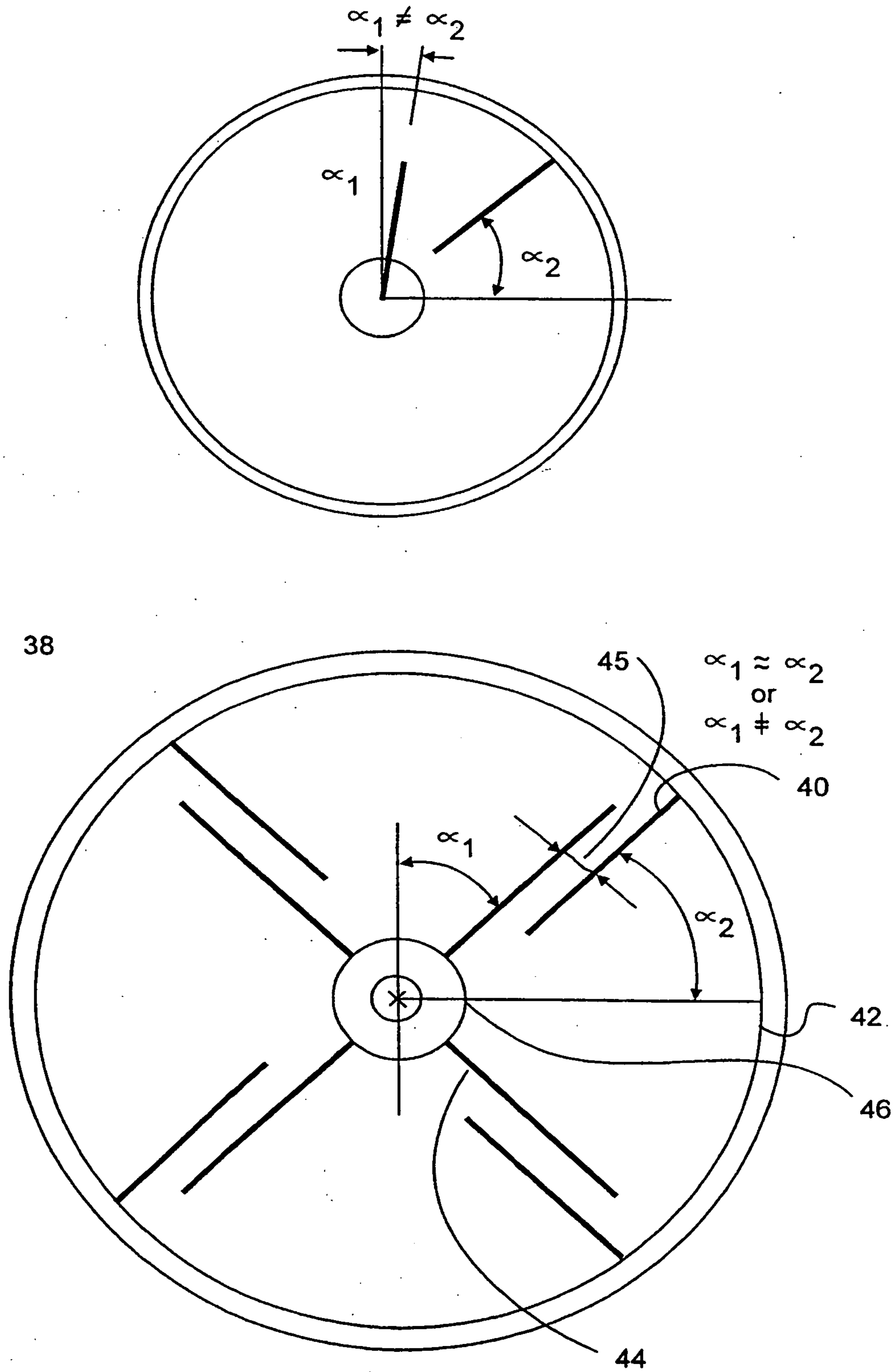
$\propto_1 \neq \propto_2$
$\propto_1$
$\propto_2$
38
45
$\propto_1 \approx \propto_2$
or
$\propto_1 \neq \propto_2$
40
$\propto_1$
$\propto_2$
42
46
44

FIG. 5

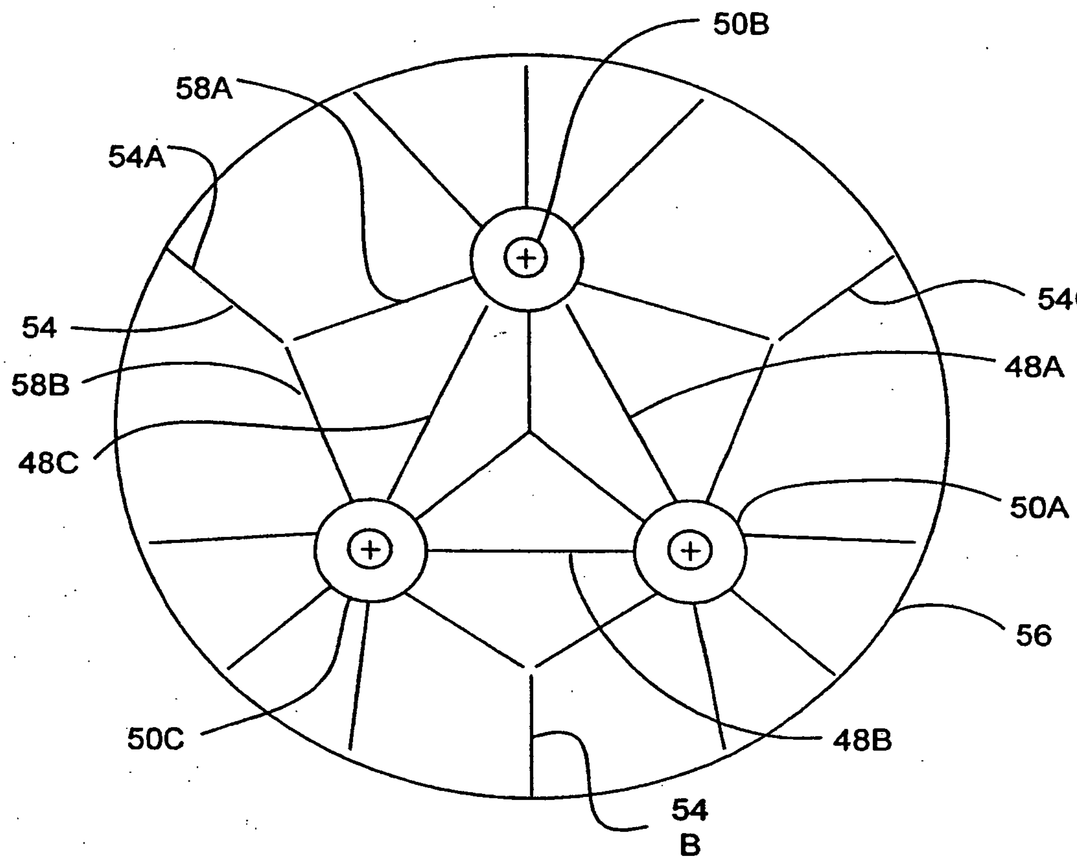

FIG. 6

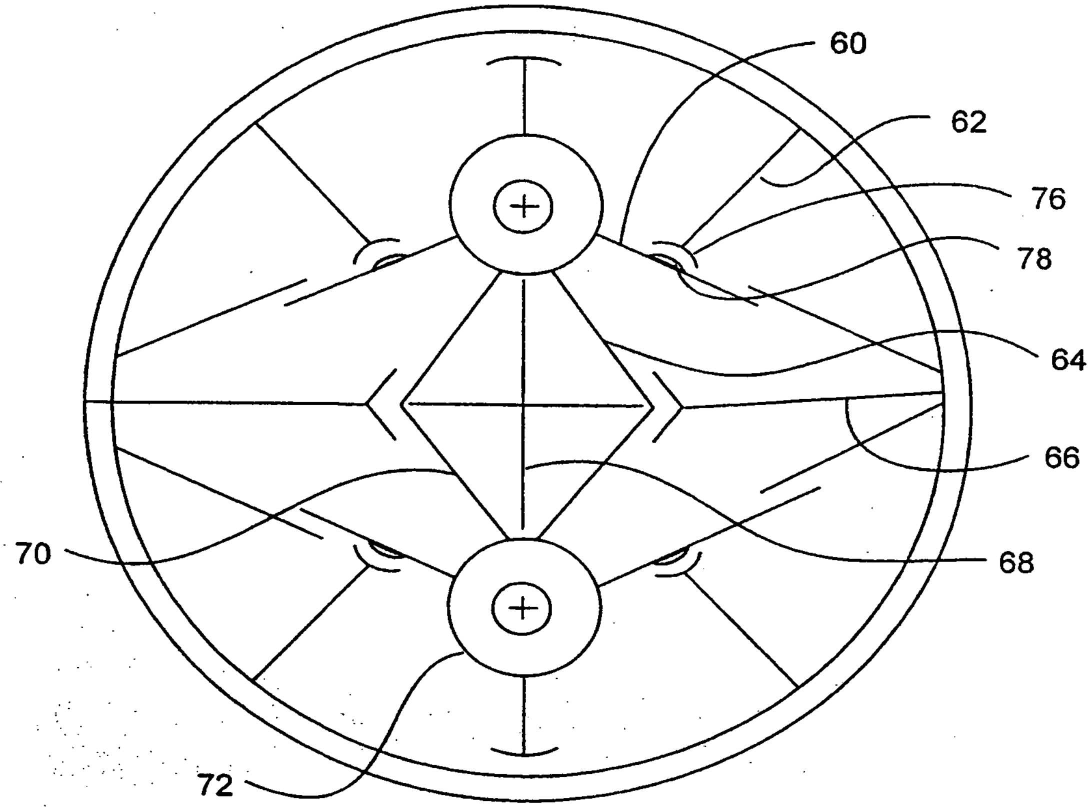

FIG. 7

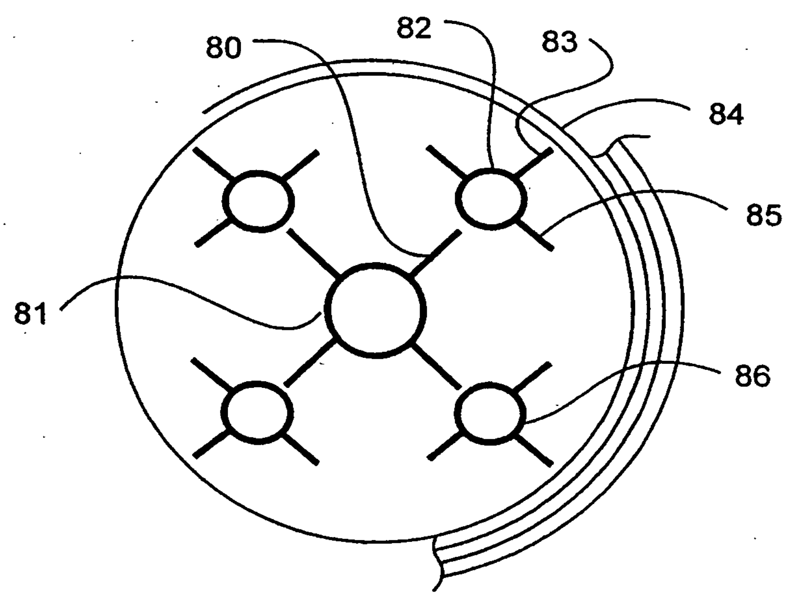

FIG. 8

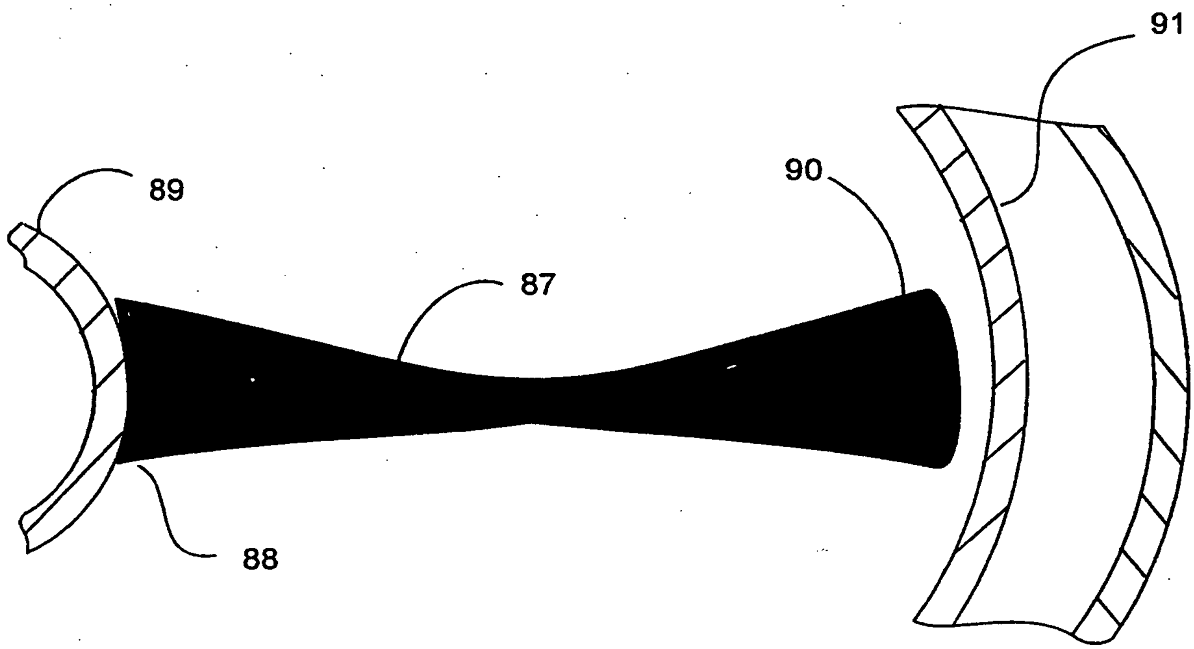

FIG. 9

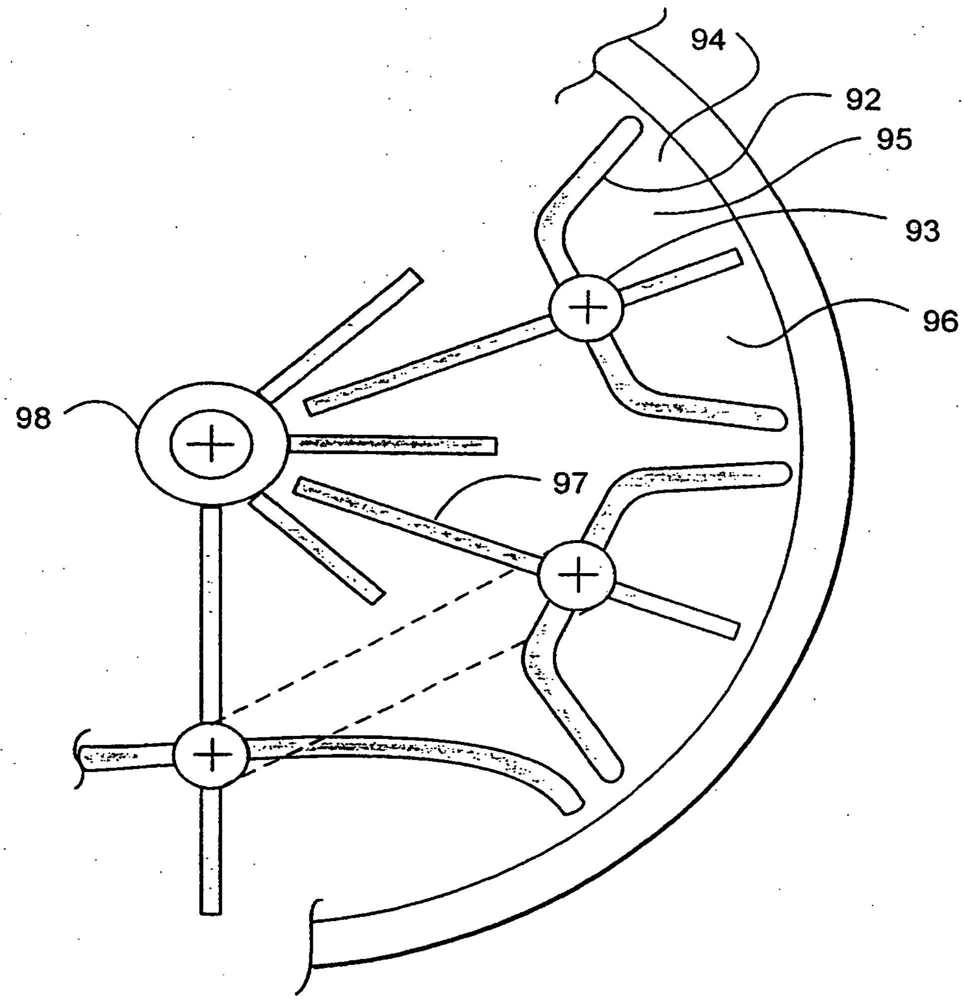

FIG. 10

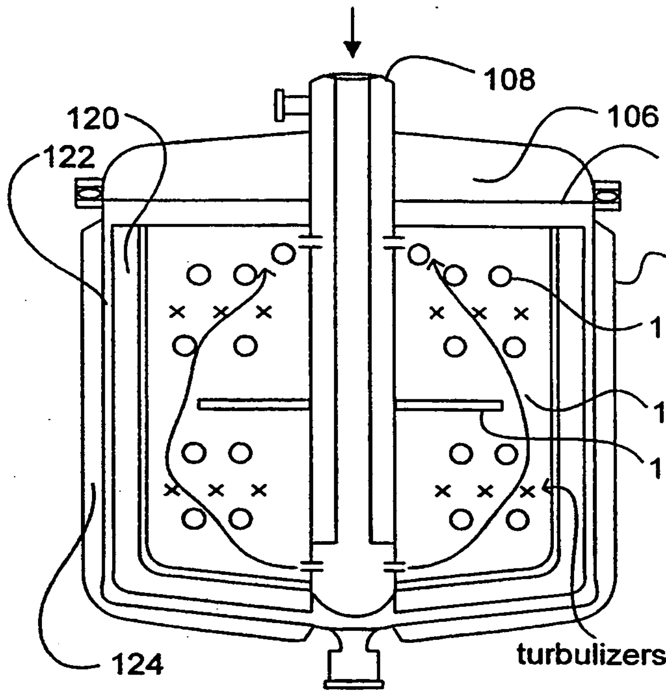

FIG. 11

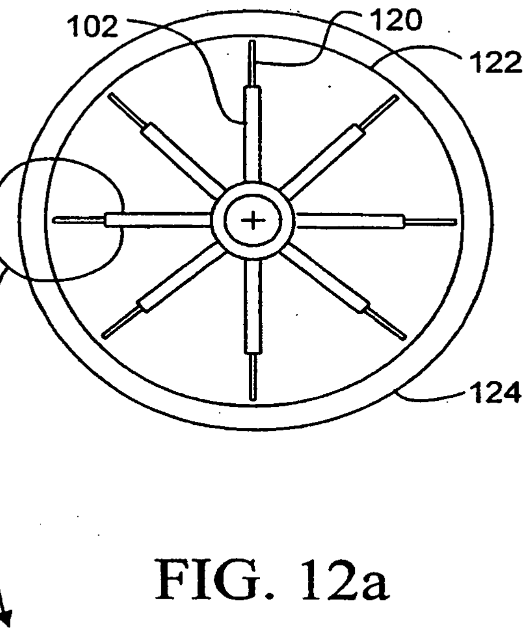

FIG. 12a

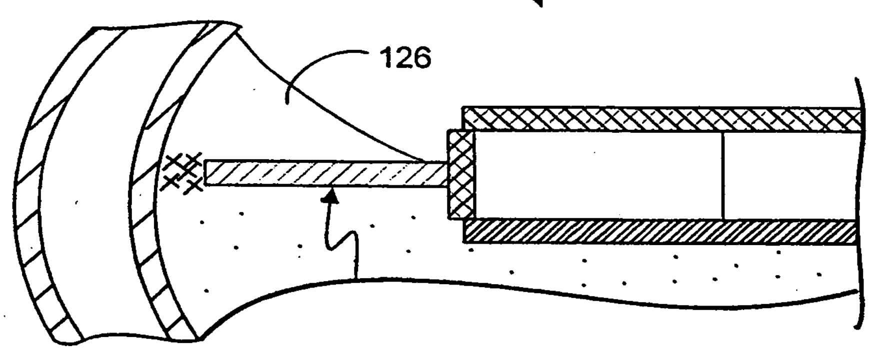

FIG. 12b

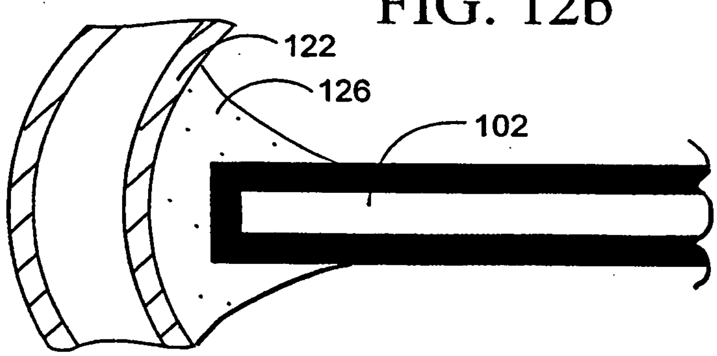

FIG. 12c

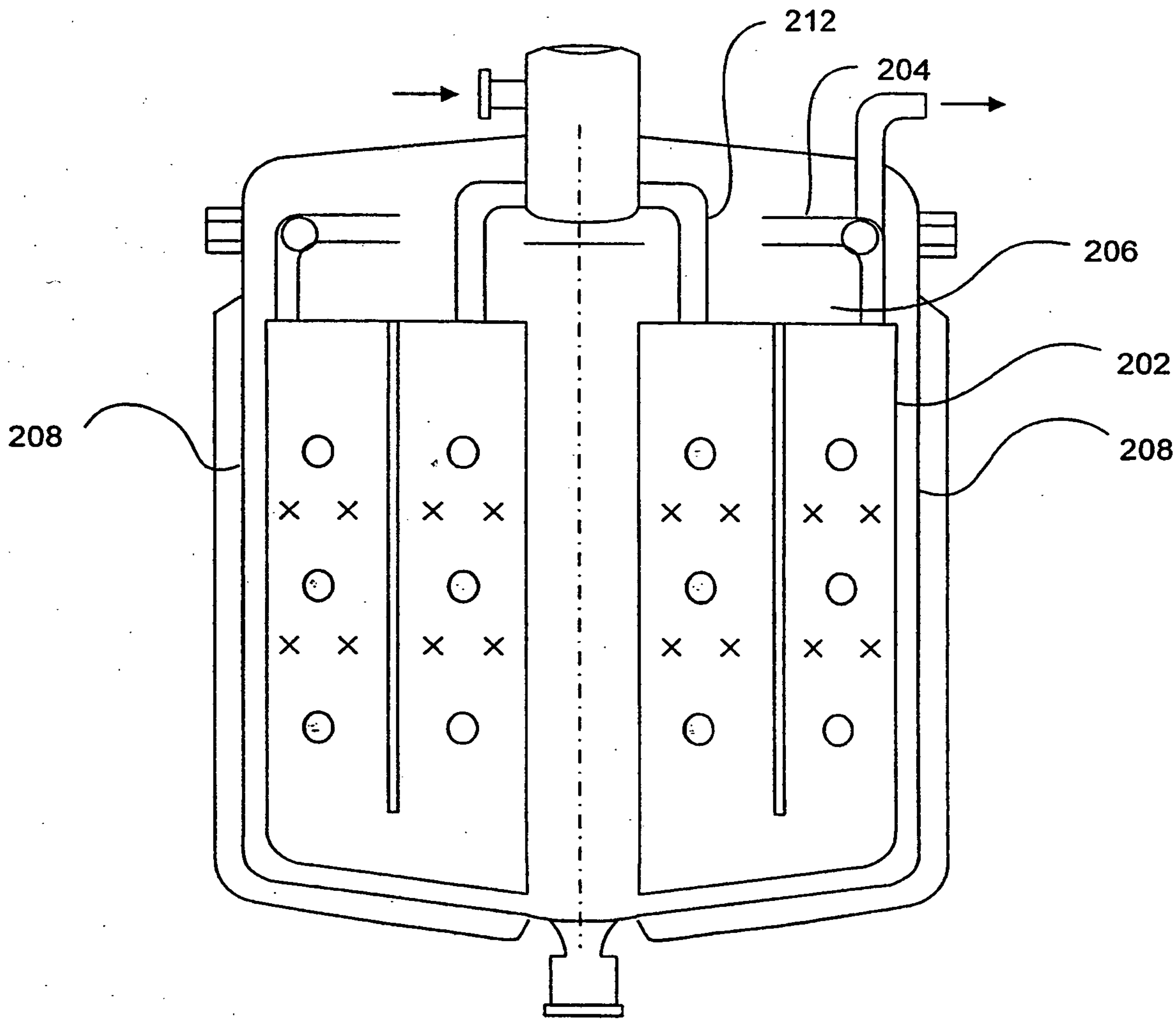

FIG. 13

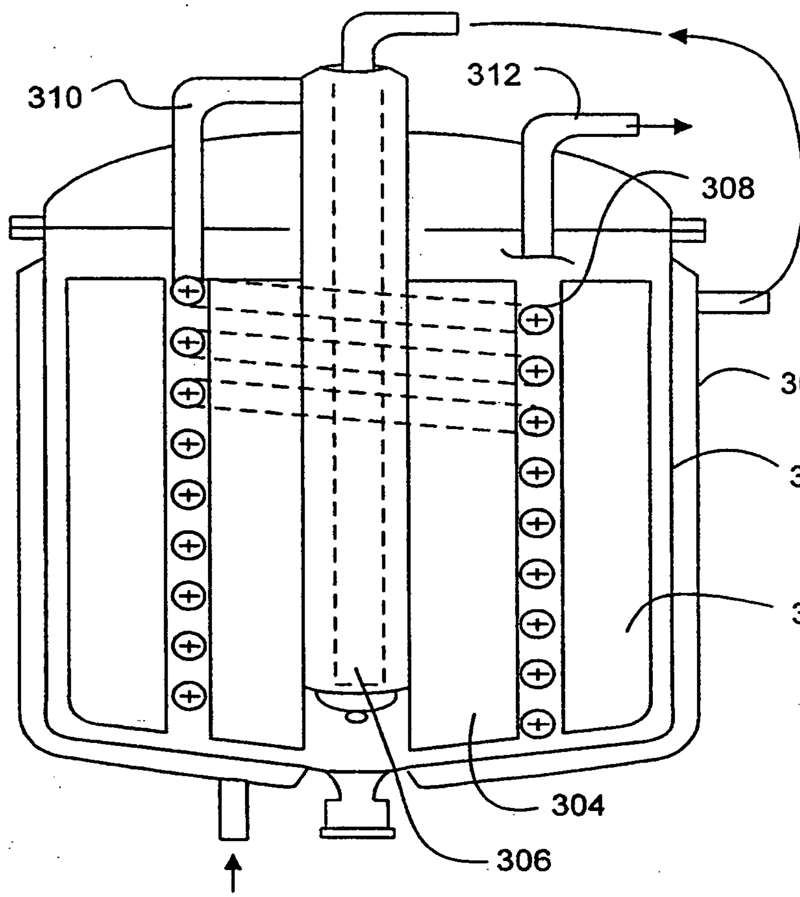

FIG. 14a

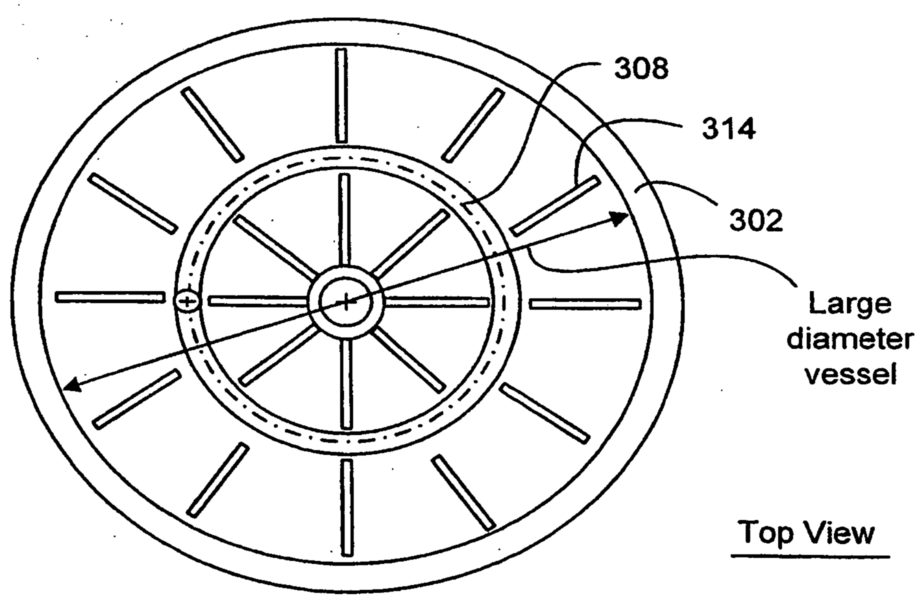

FIG. 14b

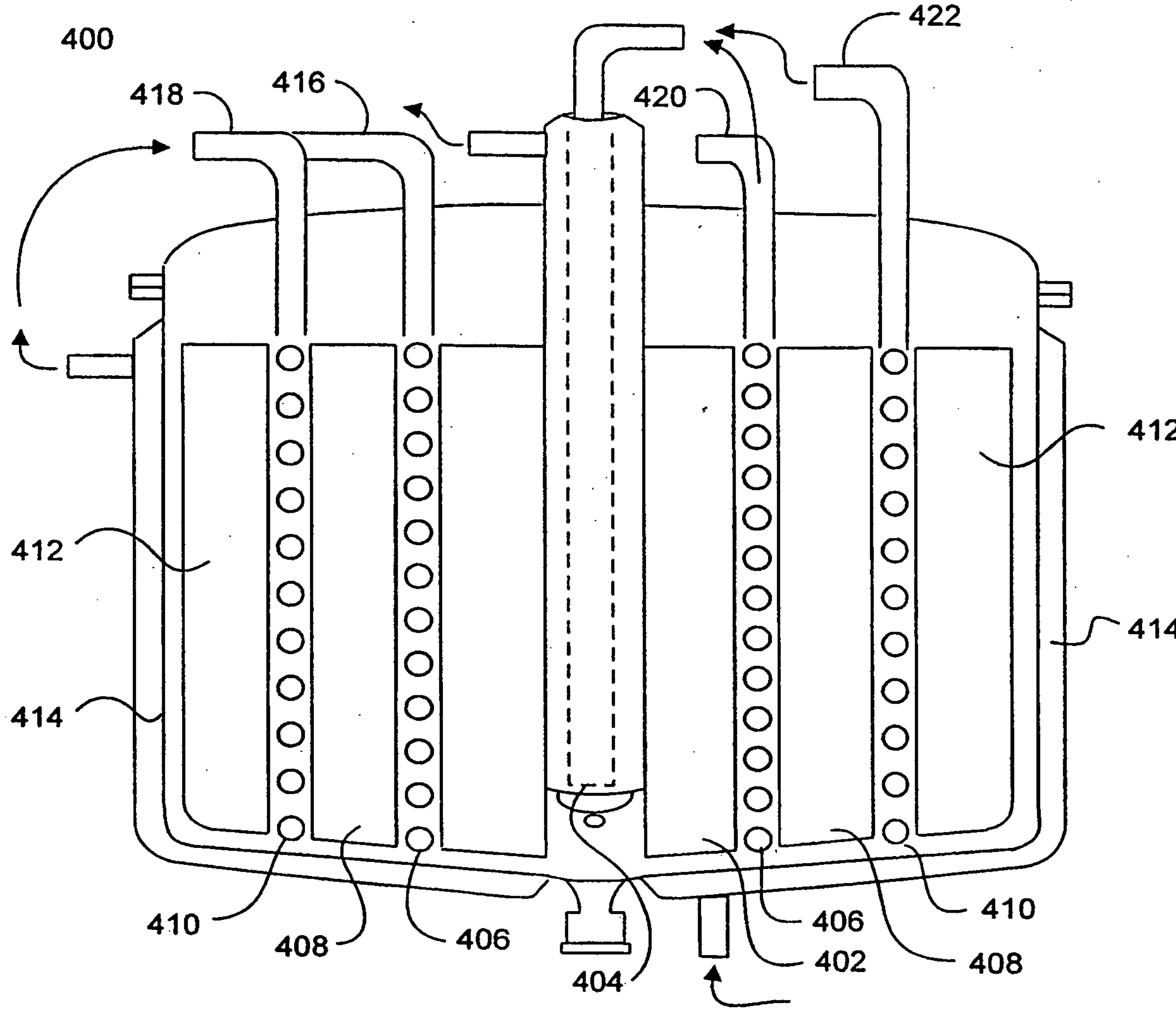

FIG. 15a

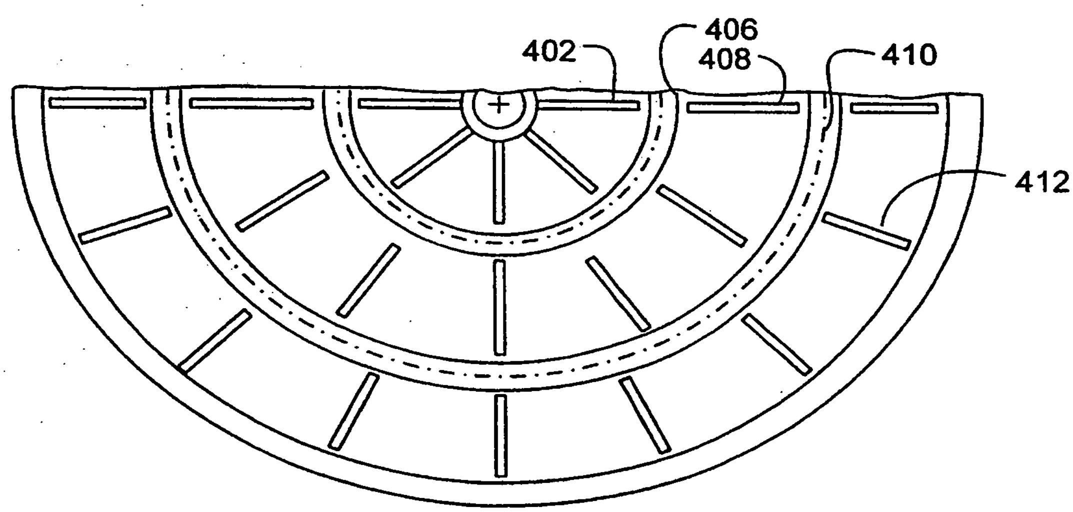

FIG. 15b

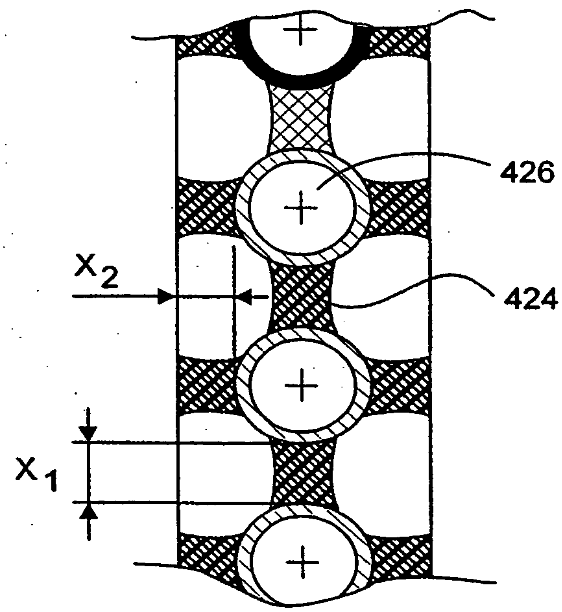

FIG. 15c

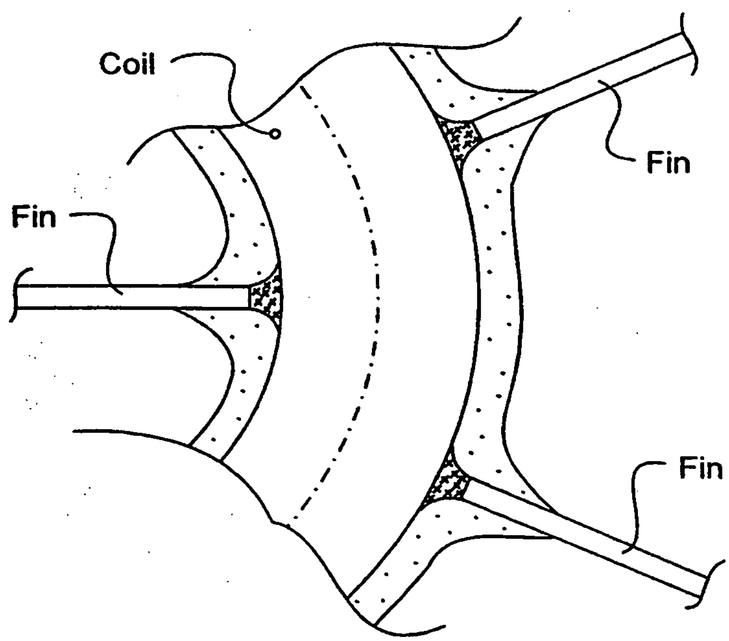

FIG. 15d

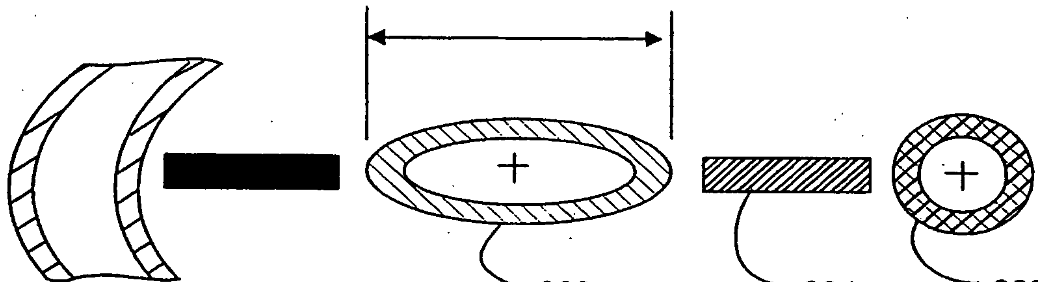

FIG.16a

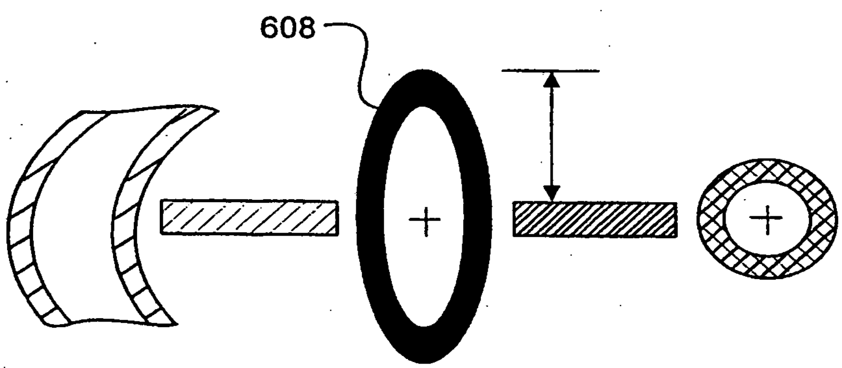

FIG.16b

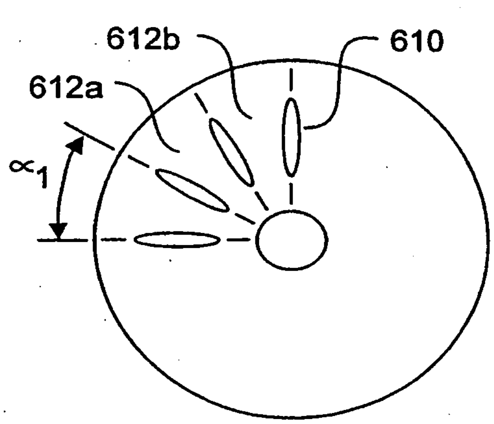

FIG. 17a

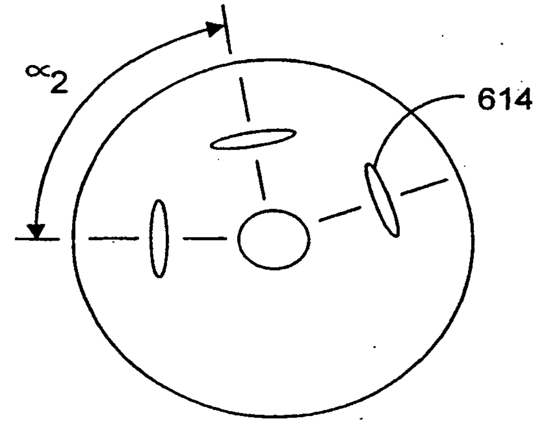

FIG. 17b

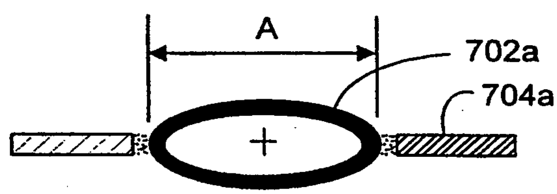

FIG. 18a

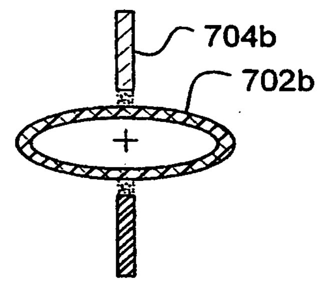

FIG. 18b

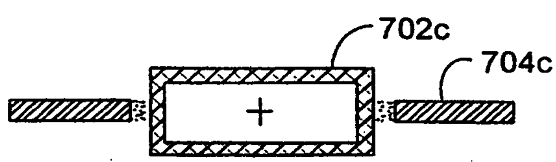

FIG. 18c

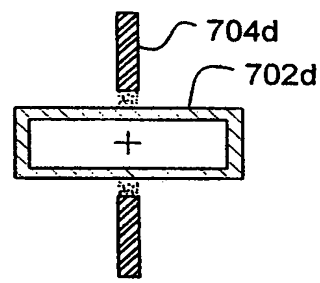

FIG. 18d

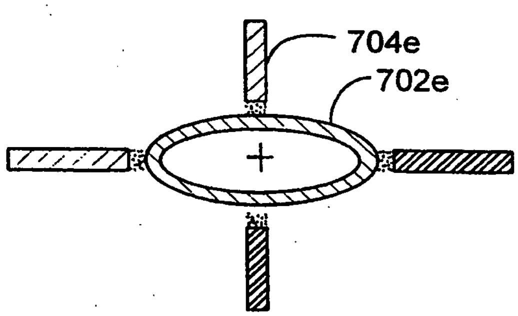

FIG. 18e

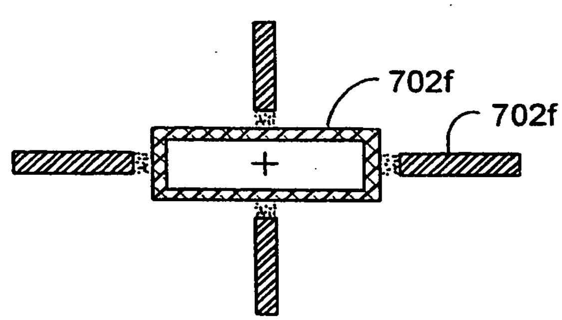

FIG. 18f

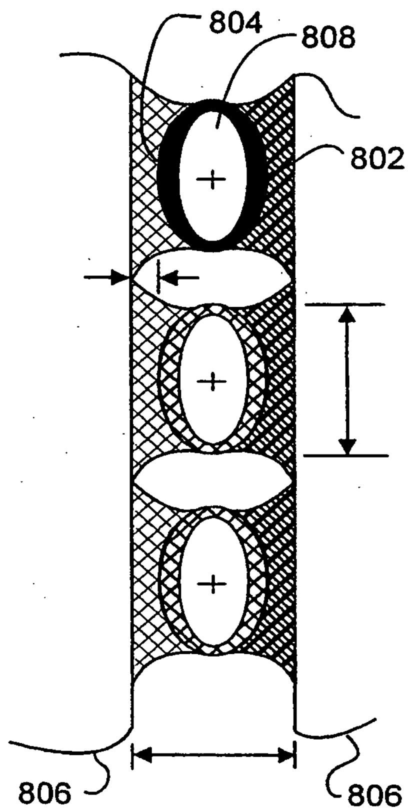

FIG. 19a

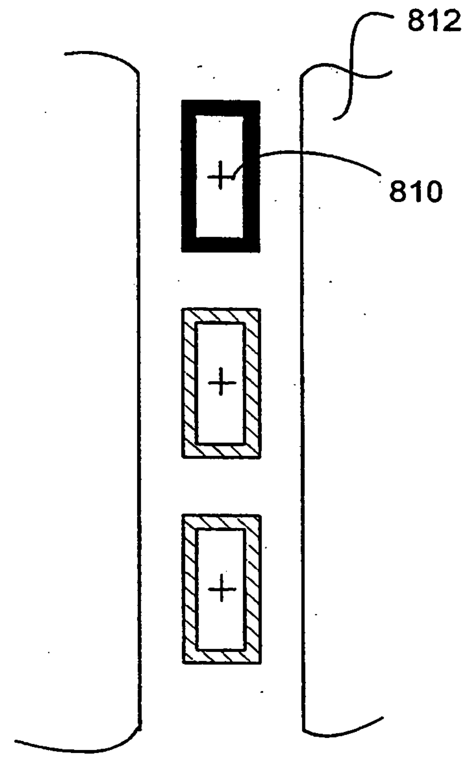

FIG. 19b

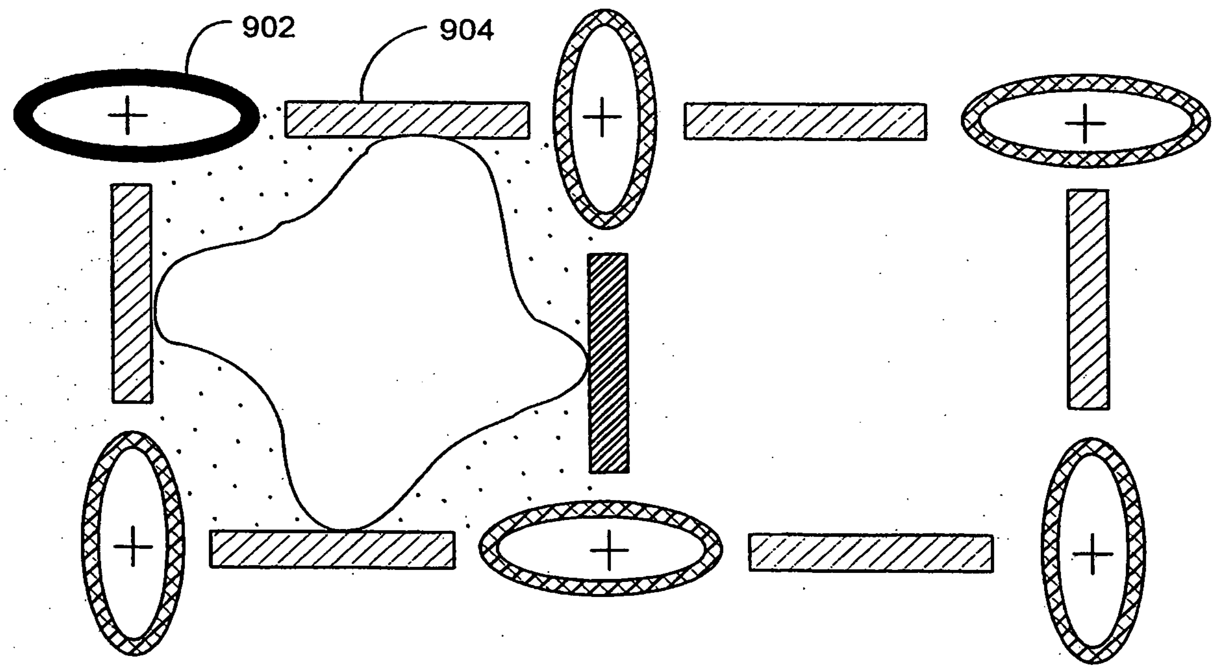

FIG. 20

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 98/02065

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 F25D31/00 F28D7/12 F28F1/14

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 F25D F25C F28D F28F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 647 707 A (SY LAB VERTRIEBSGES M B H) 12 April 1995 see column 3, line 49 - column 5, line 38; figures 1-3	1,2,5, 18,19, 42,43, 63,64
A	GB 518 301 A (THE LIGHTFOOT REFRIGERATION COMPANY) 22 February 1940 see page 4, line 3 - page 5, line 50; figures 1-4	1,18,42, 63

-/--

[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier document but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art.

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
19 June 1998	25/06/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Boets, A

1

Form PCT/ISA/210 (second sheet) (July 1992)

INTERNATIONAL SEARCH REPORT

Inte...ational Application No
PCT/US 98/02065

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 3 595 308 A (DURBIN LEWIS H) 27 July 1971 see column 1, line 71 - column 4, line 23; figures 1-4	1,11,18, 22,27, 28,30, 35,42, 45,47, 55,57, 63,80,82
A	US 3 764 780 A (ELLIS C) 9 October 1973 see column 1, line 63 - column 4, line 46; figures 1-5	1,18,42, 63
A	US 2 405 091 A (CULBRETH ALEXANDER M) 30 July 1946 see column 1, line 51 - column 2, line 51; figures 1-5	1,18,42, 63
A	US 3 108 840 A (CONRAD EDWIN O) 29 October 1963 see column 3, line 54 - column 7, line 32; figures 1-17	1,18,42, 63
A	US 2 449 343 A (TORBENSEN VIGGO V) 14 September 1948 see column 1, line 47 - column 3, line 40; figures 1-4	10,26, 53,74
A	US 5 168 725 A (MARGOLIN ELY) 8 December 1992	
A	US 2 441 376 A (STIENING FRANK H) 11 May 1948	
A	FR 2 237 156 A (MONTAGNE LOUIS) 7 February 1975	
A	EP 0 618 413 A (WELCH DANIEL LEE ;LOVE JEFF LINDEN (US)) 5 October 1994	

1

INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/US 98/02065

Patent document cited in search report		Publication date	Patent family member(s)			Publication date
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			AT	168493	A	15-02-1996
			US	5635397	A	03-06-1997
GB 518301	A		NONE			
US 3595308	A	27-07-1971	NONE			
US 3764780	A	09-10-1973	NONE			
US 2405091	A	30-07-1946	NONE			
US 3108840	A	29-10-1963	NONE			
US 2449343	A	14-09-1948	NONE			
US 5168725	A	08-12-1992	WO	9316591	A	02-09-1993
US 2441376	A	11-05-1948	NONE			
FR 2237156	A	07-02-1975	FR	2260076	A	29-08-1975
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			AU	669263	B	30-05-1996
			AU	5910094	A	06-10-1994
			CA	2120110	A	01-10-1994
			DE	69401290	D	13-02-1997
			DE	69401290	T	10-07-1997
			ES	2098810	T	01-05-1997
			US	5379603	A	10-01-1995
			US	5555734	A	17-09-1996

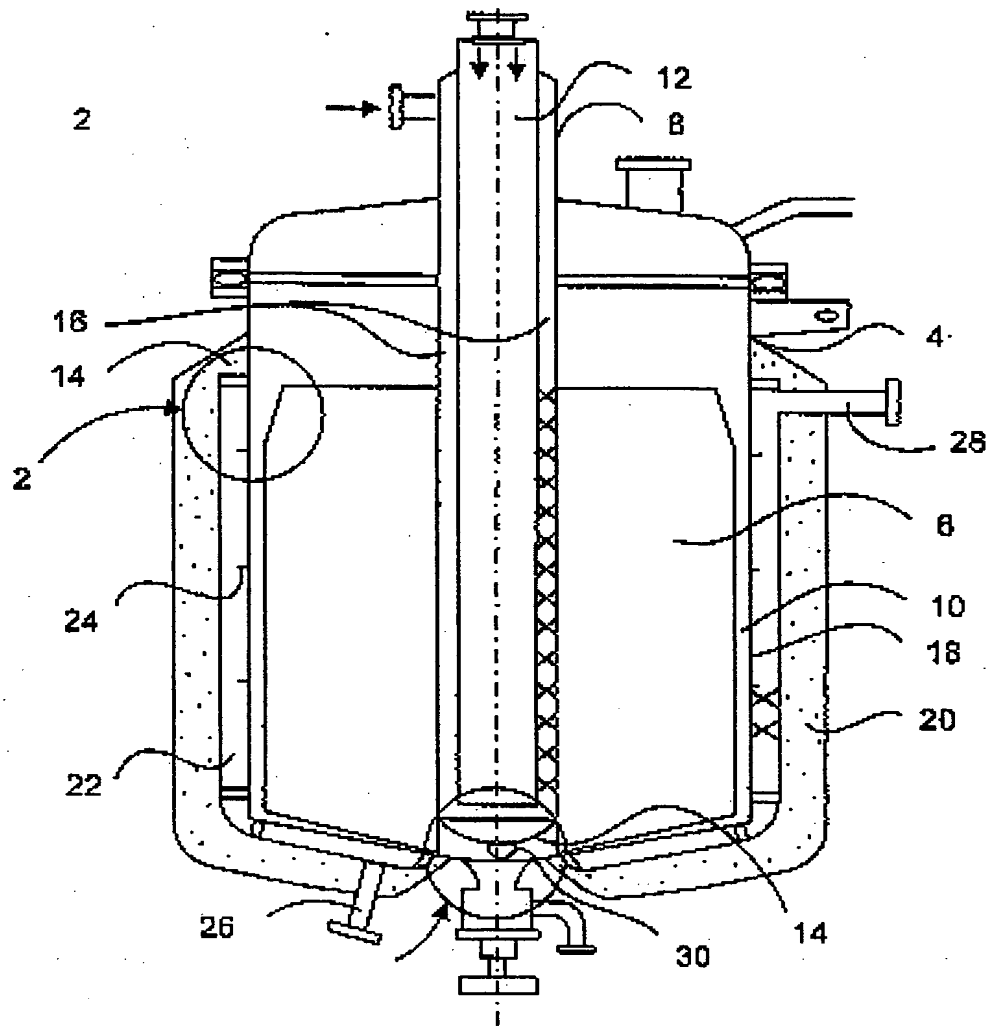


FIG. 1

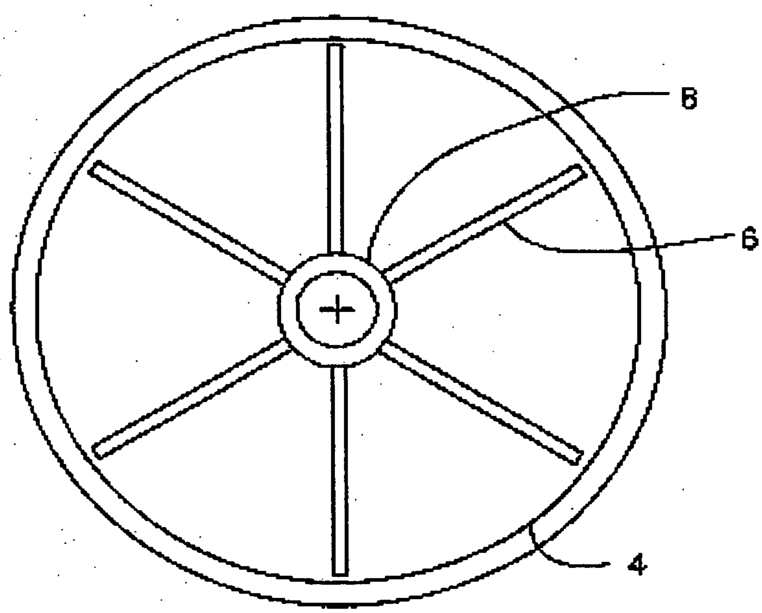


FIG. 2

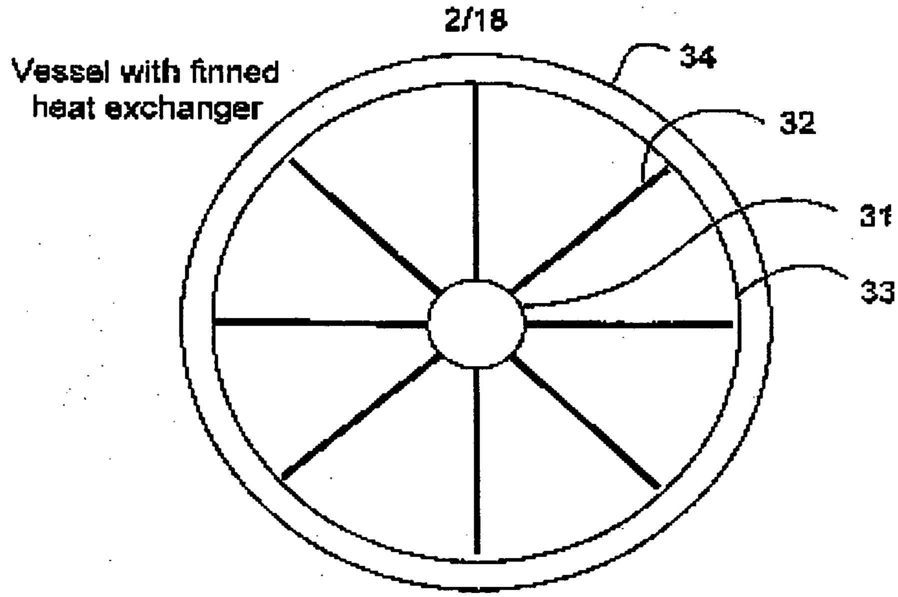

Vessel with finned heat exchanger
34
32
31
33

FIG. 3a

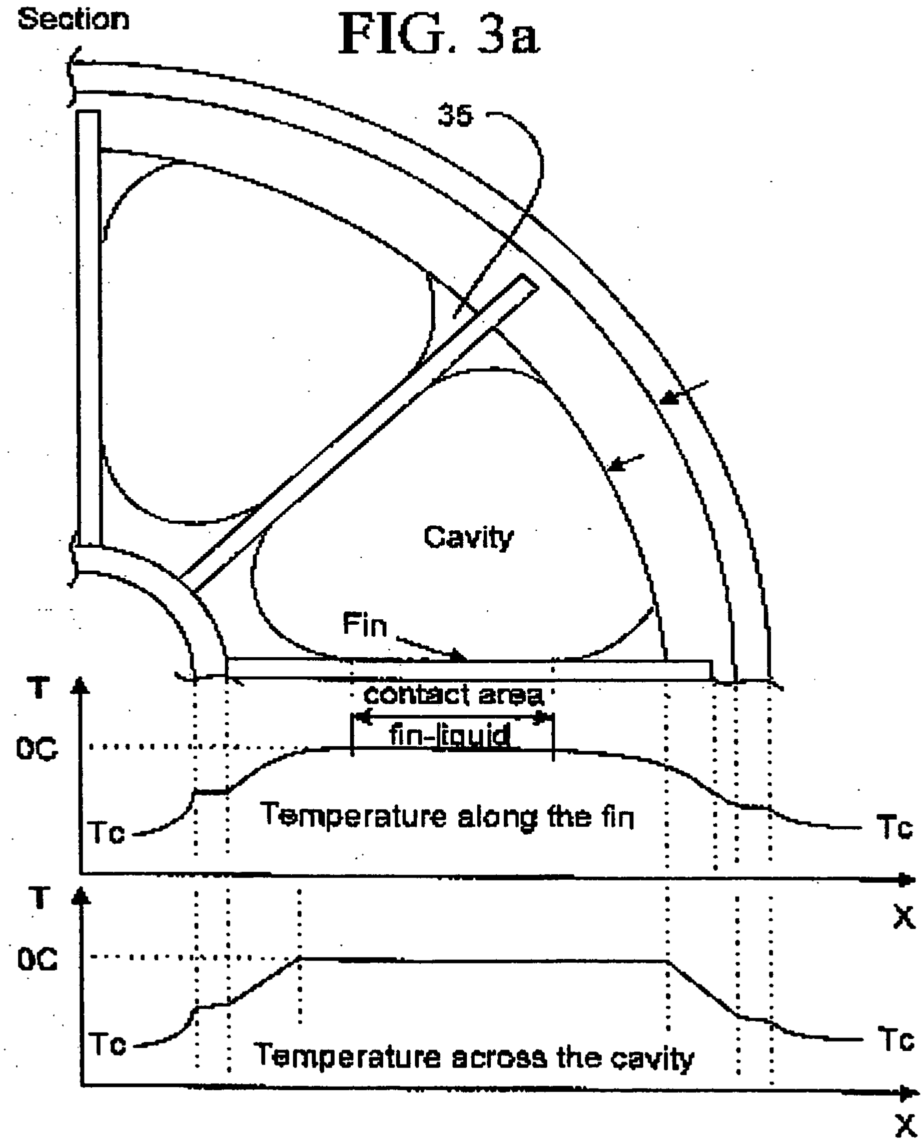

Section
35
Cavity
Fin
contact area
fin-liquid
T
0C
Tc
Temperature along the fin
Tc
X
T
0C
Tc
Temperature across the cavity
Tc
X

FIG. 3b

Section of the vessel with internal finned Heat exchanger

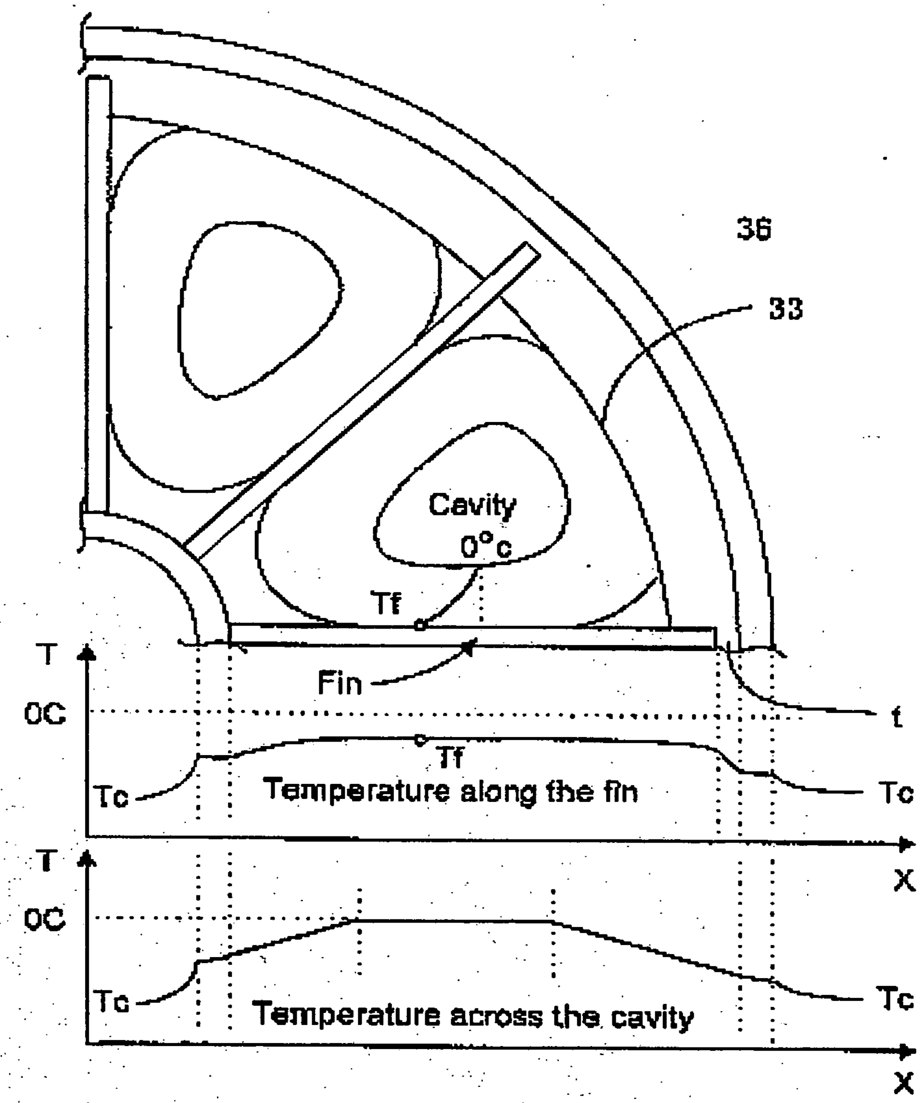


FIG. 3c

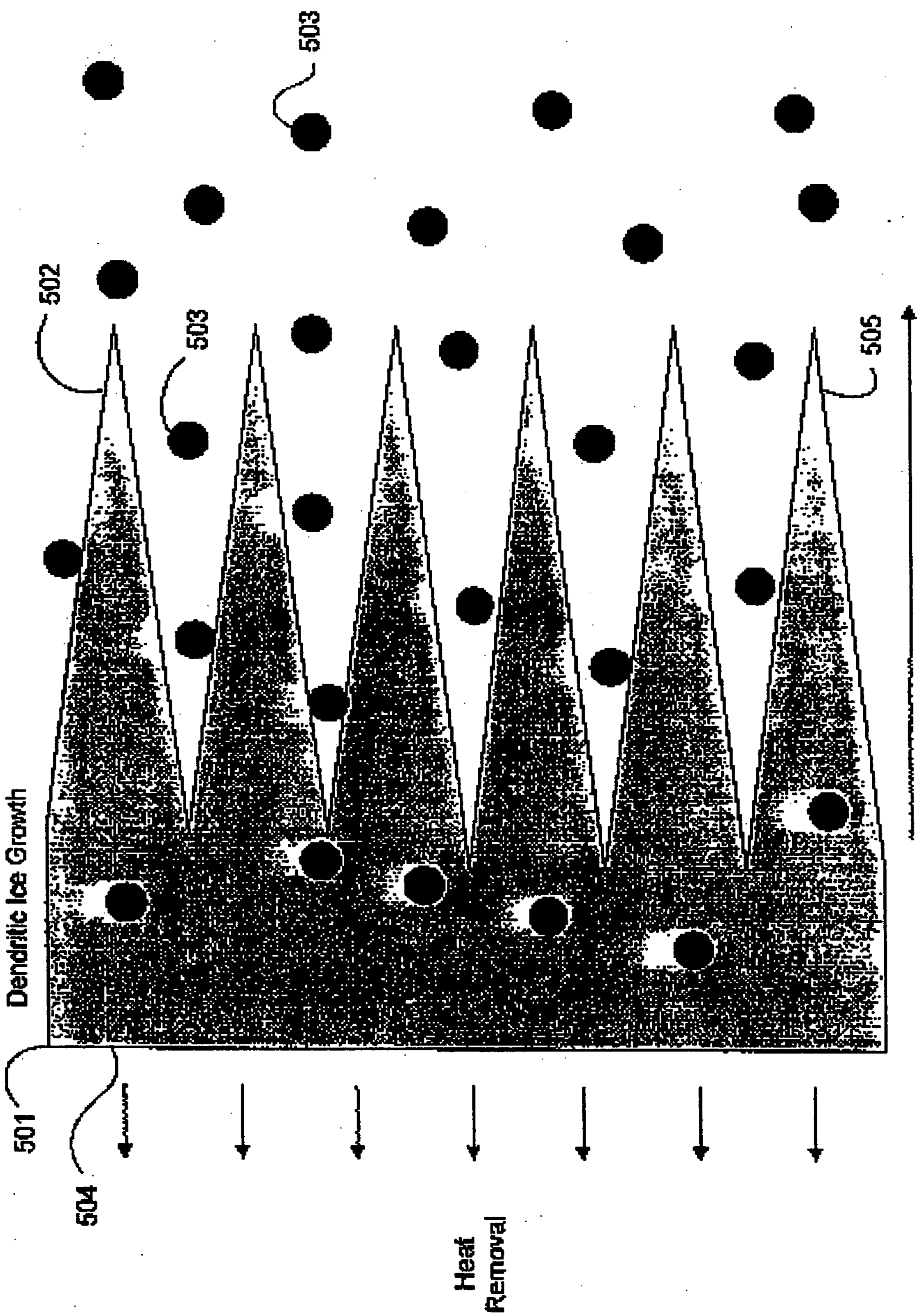

503
502
503
505
Dendritic Ice Growth
Front Growth
501
504
Heat Removal

FIG. 3d

Section of the vessel with internal finned Heat exchanger

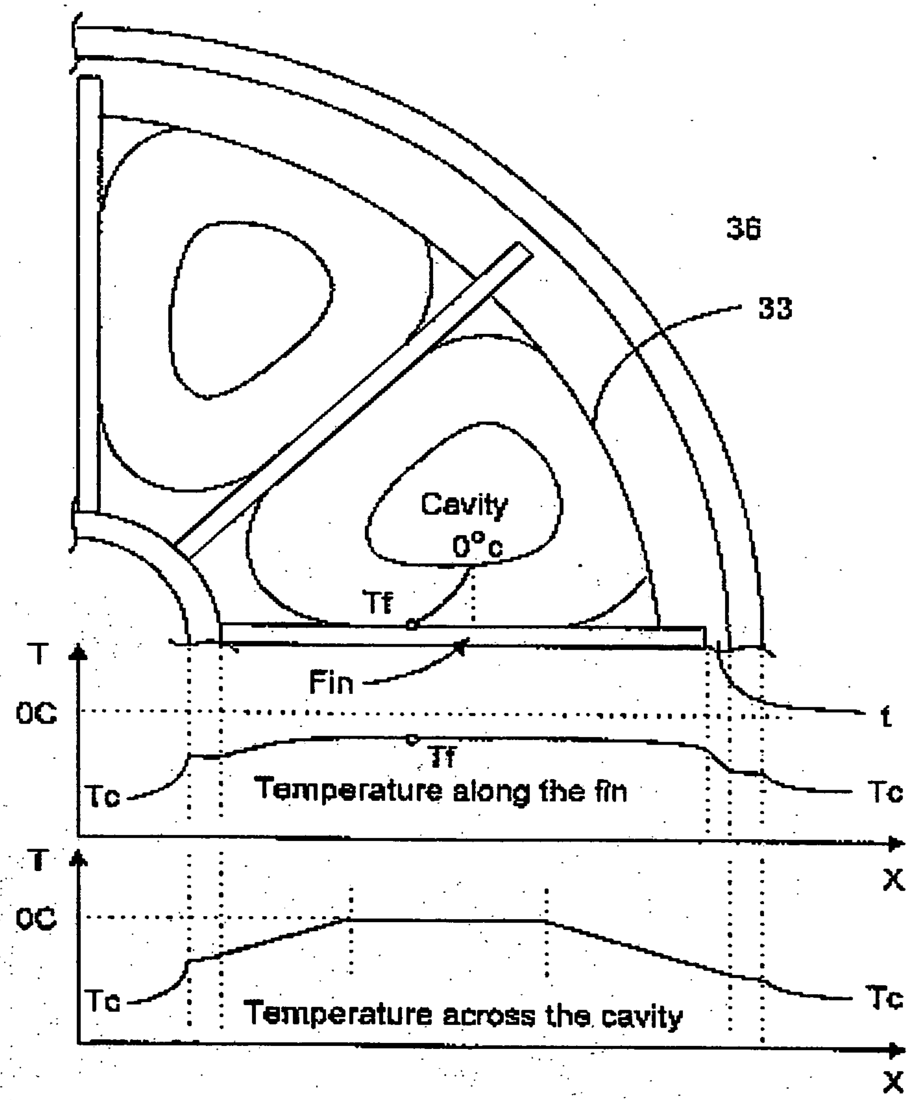


FIG. 3c

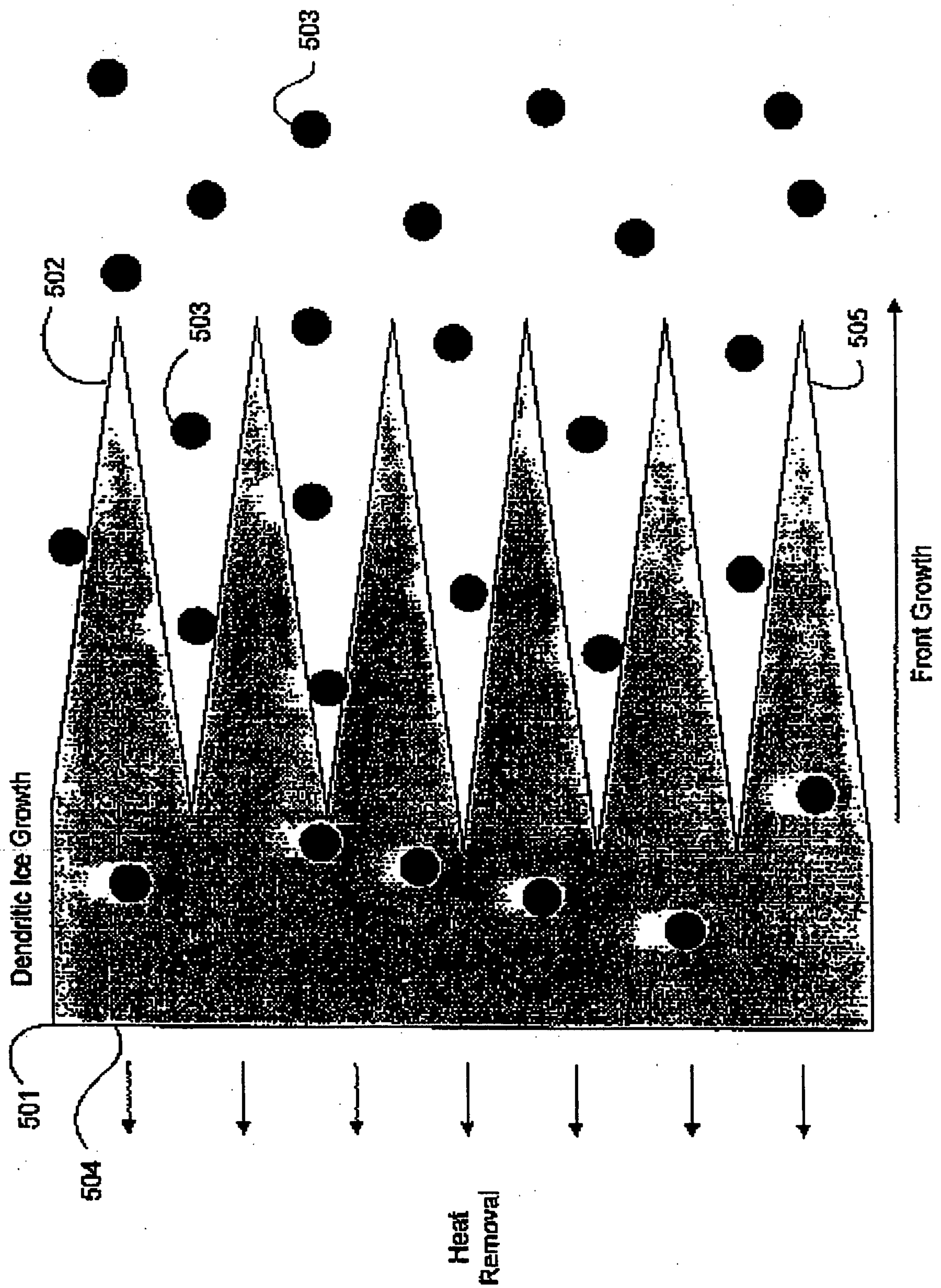

503
502
503
505
Dendritic Ice Growth
Front Growth
501
504
Heat Removal

FIG. 3d

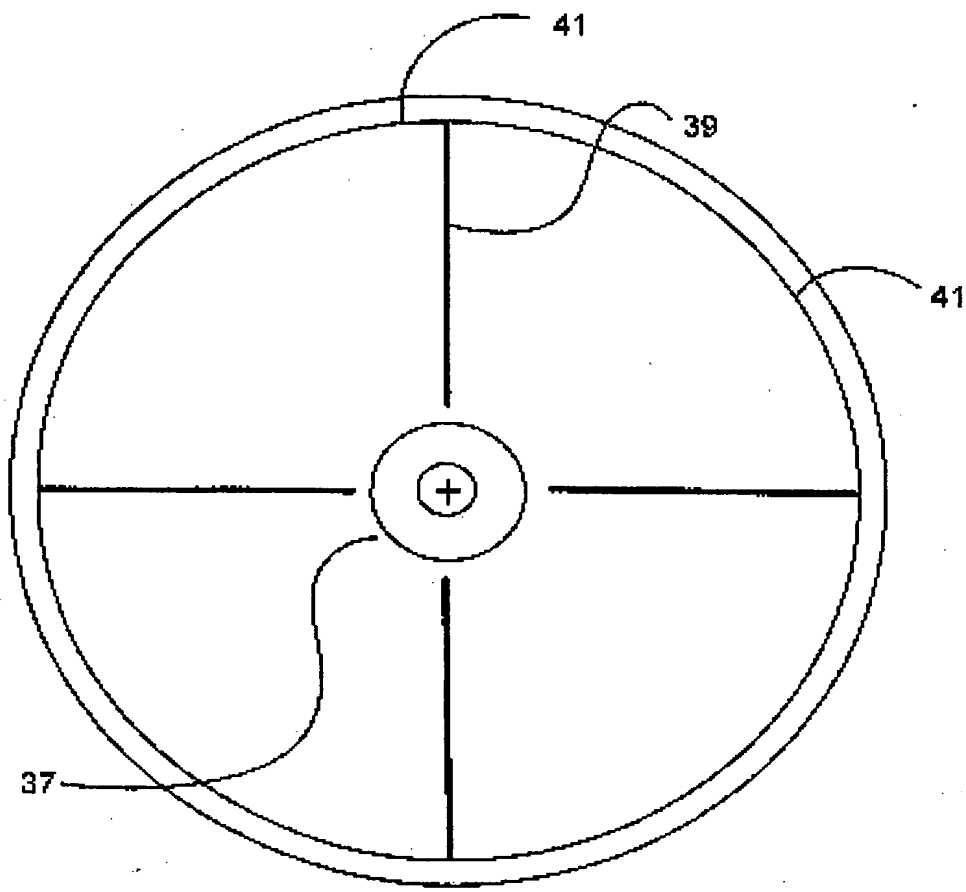
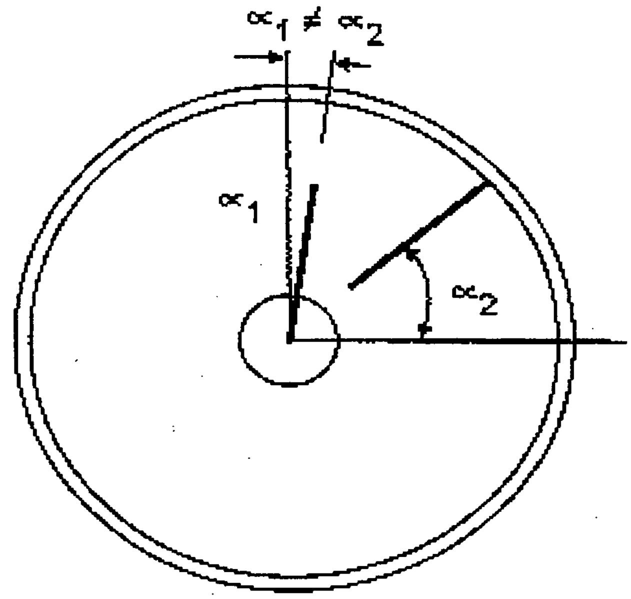


FIG. 4


$\alpha_1 \neq \alpha_2$
α_1
α_2

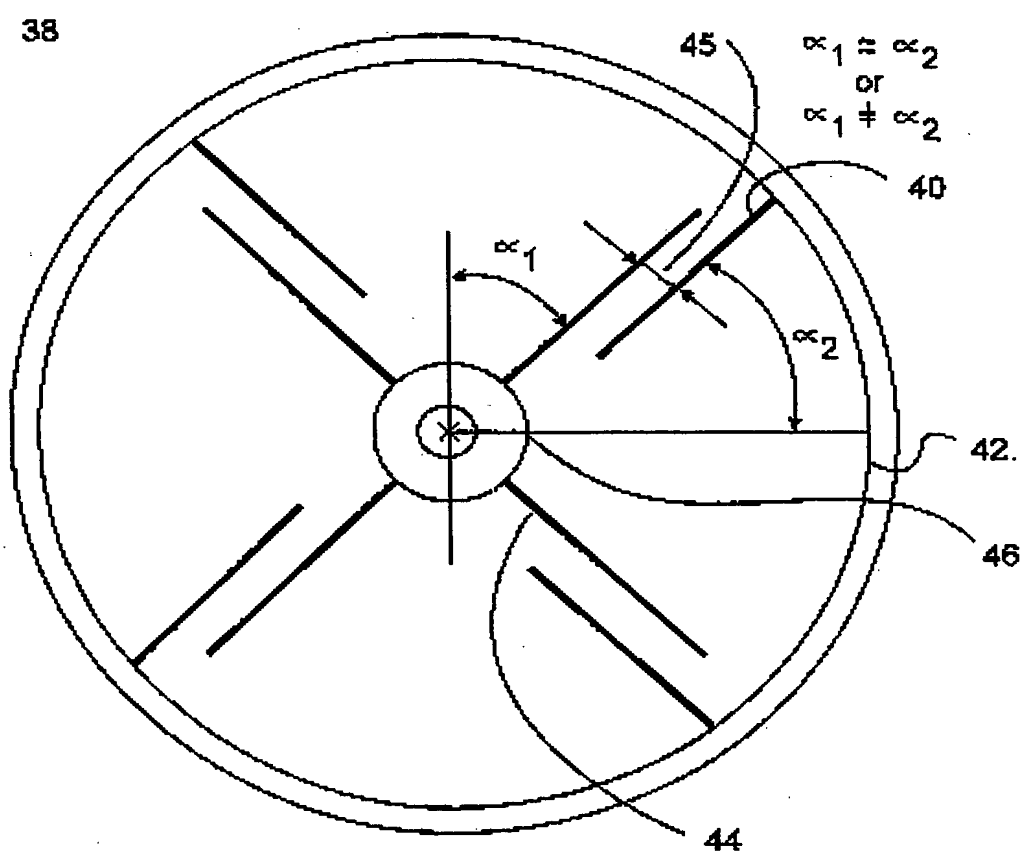

38
45
$\alpha_1 \approx \alpha_2$
or
$\alpha_1 \neq \alpha_2$
40
α_1
α_2
42.
46
44

FIG. 5

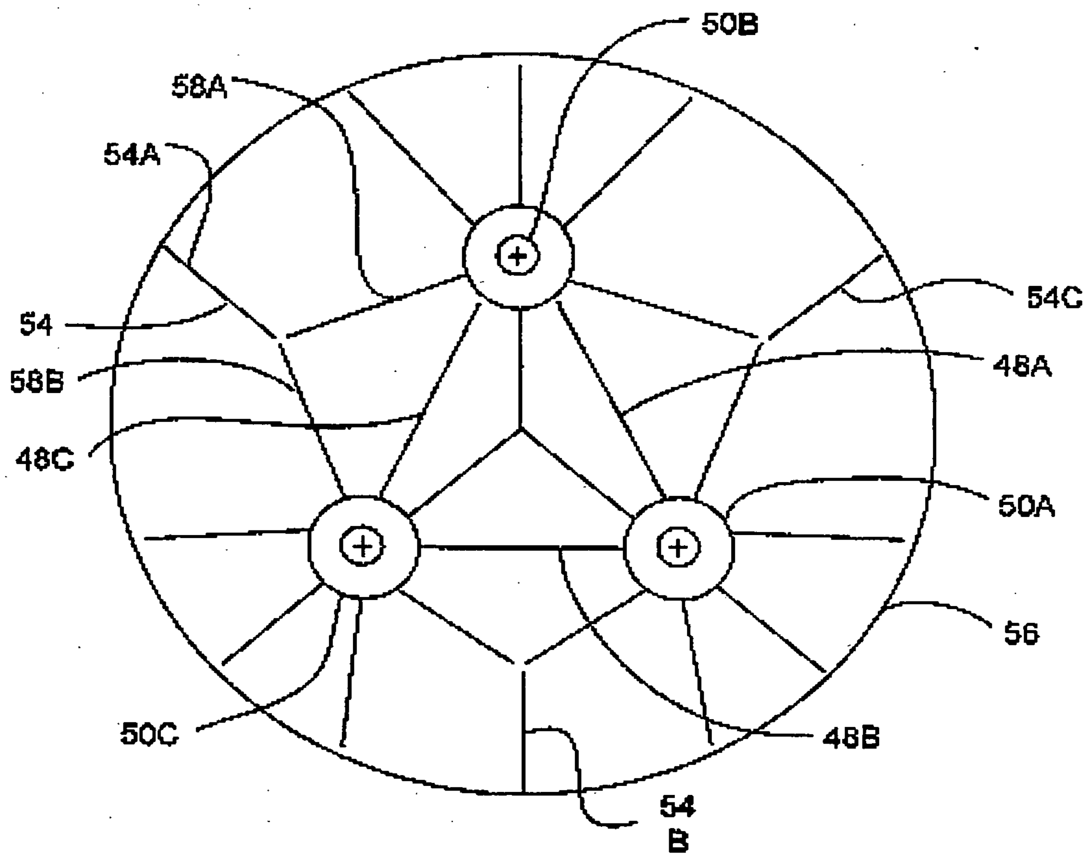


FIG. 6

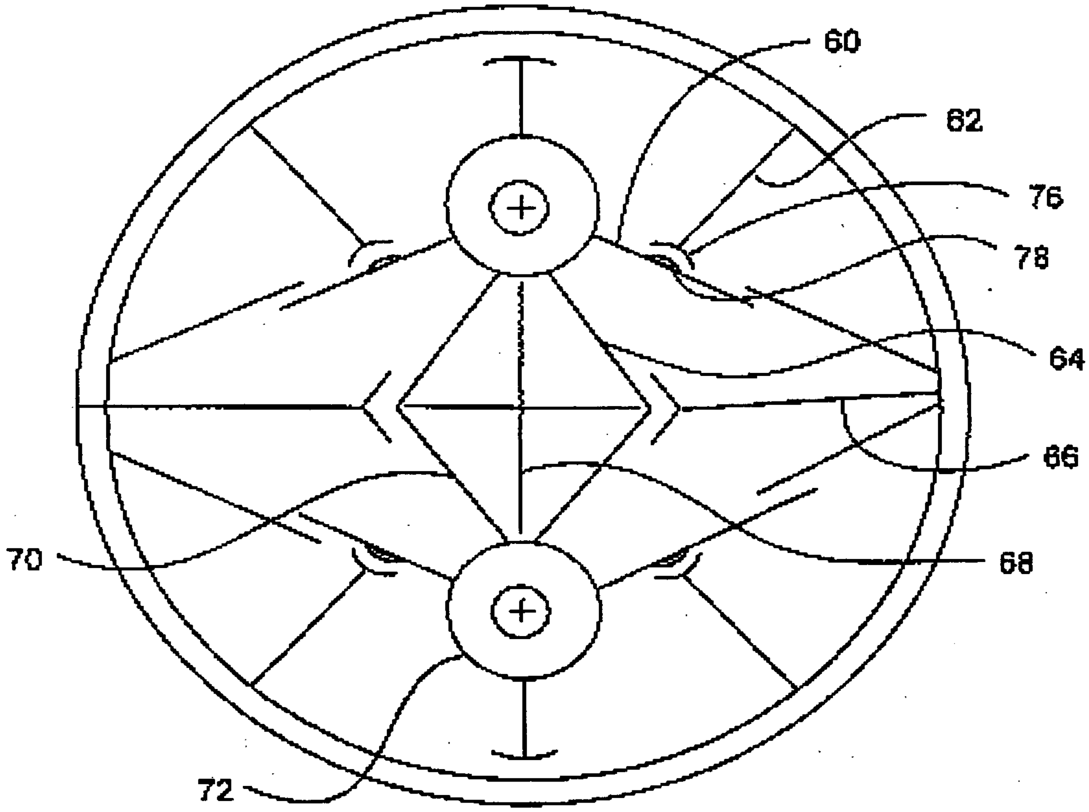


FIG. 7

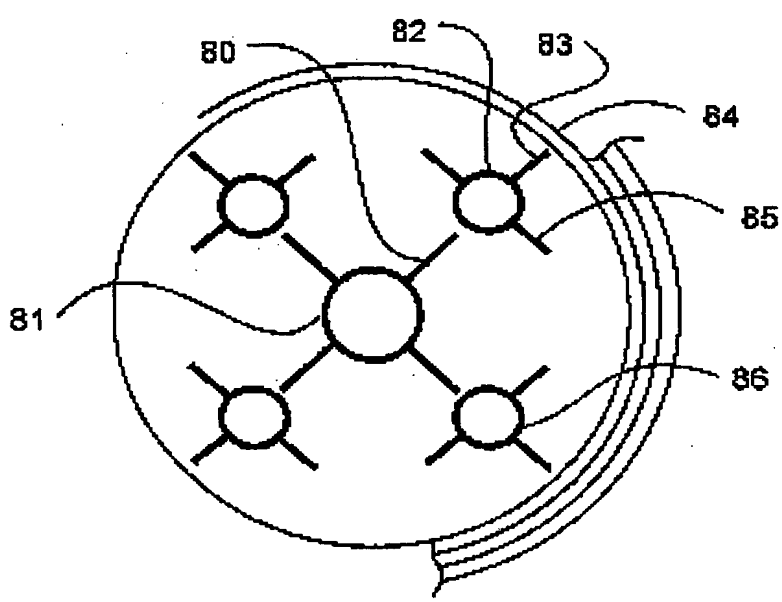


FIG. 8

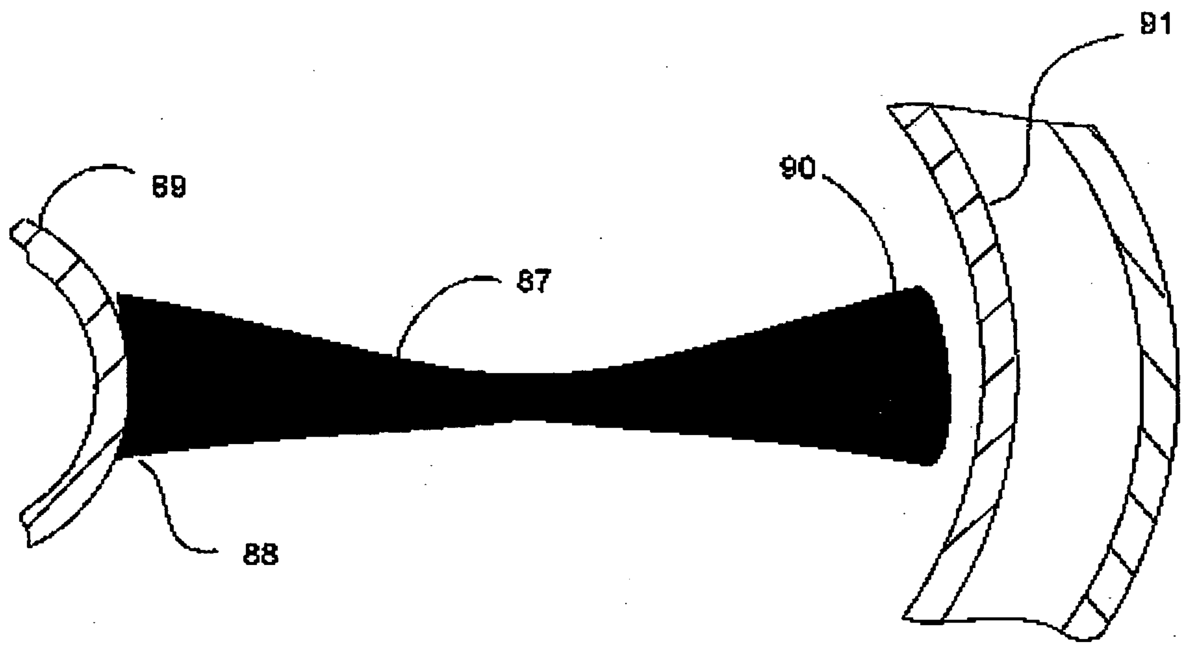


FIG. 9

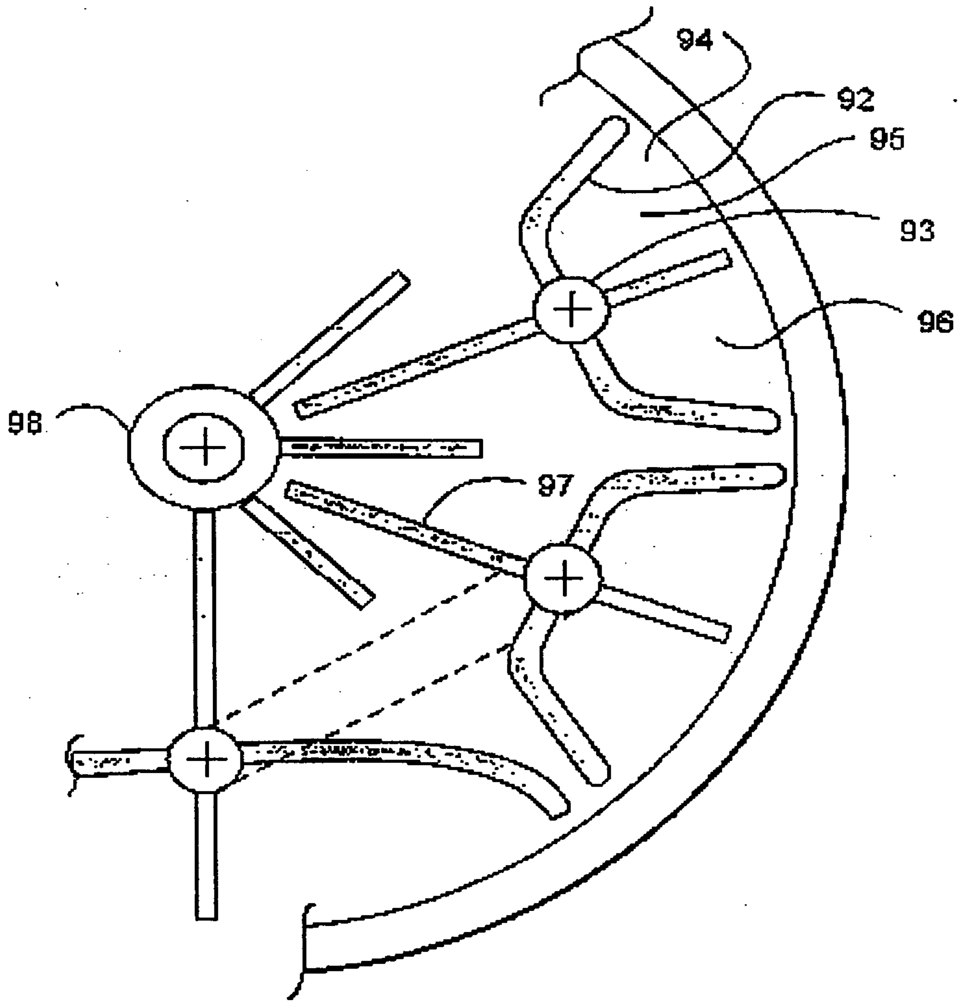


FIG. 10

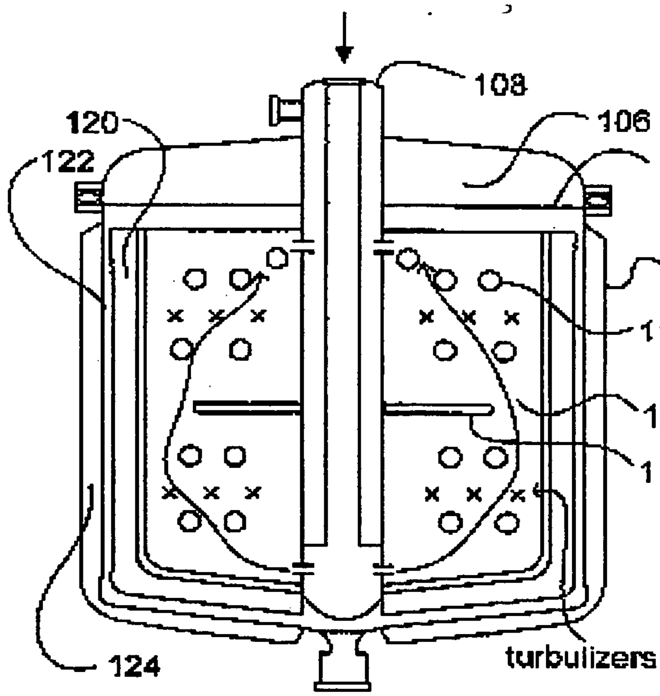


FIG. 11

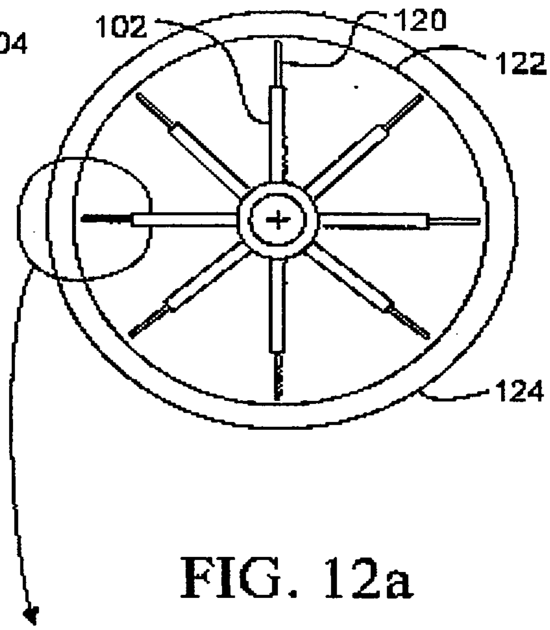


FIG. 12a

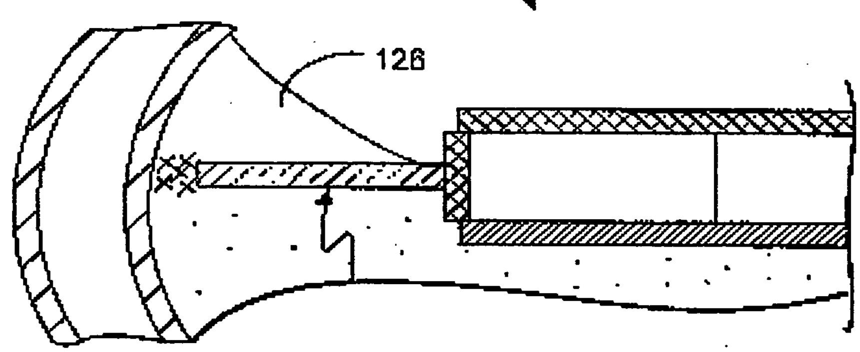


FIG. 12b

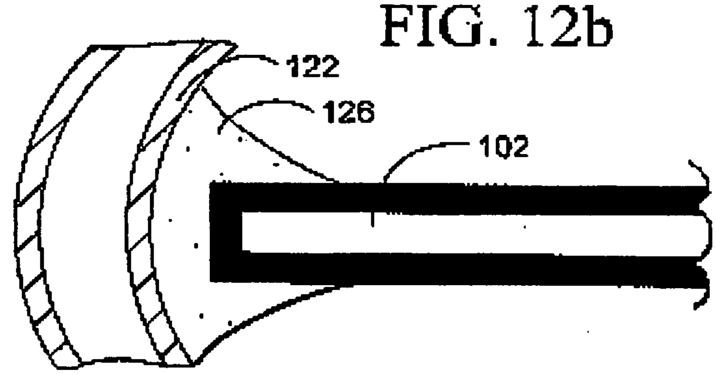


FIG. 12c

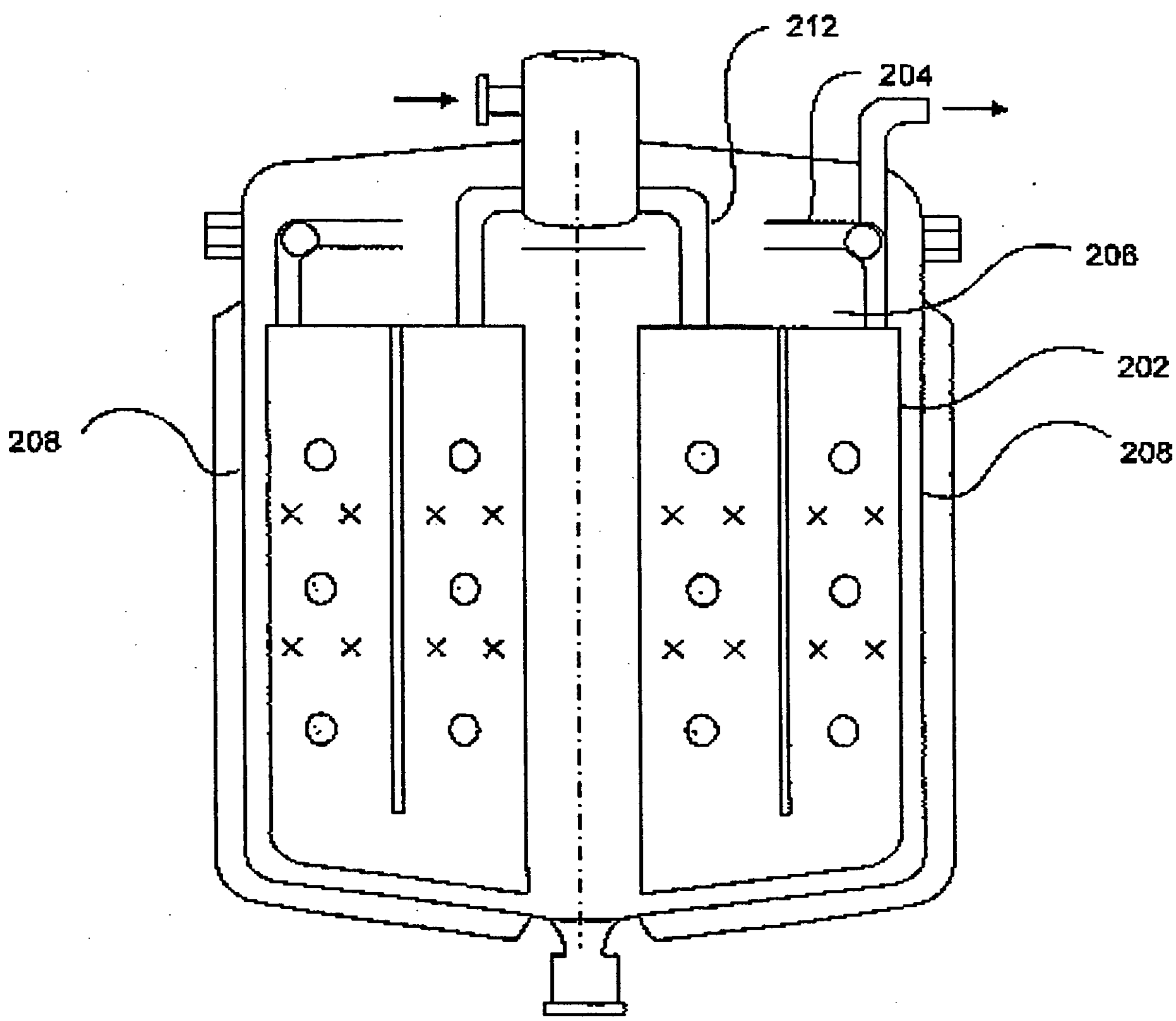


FIG. 13

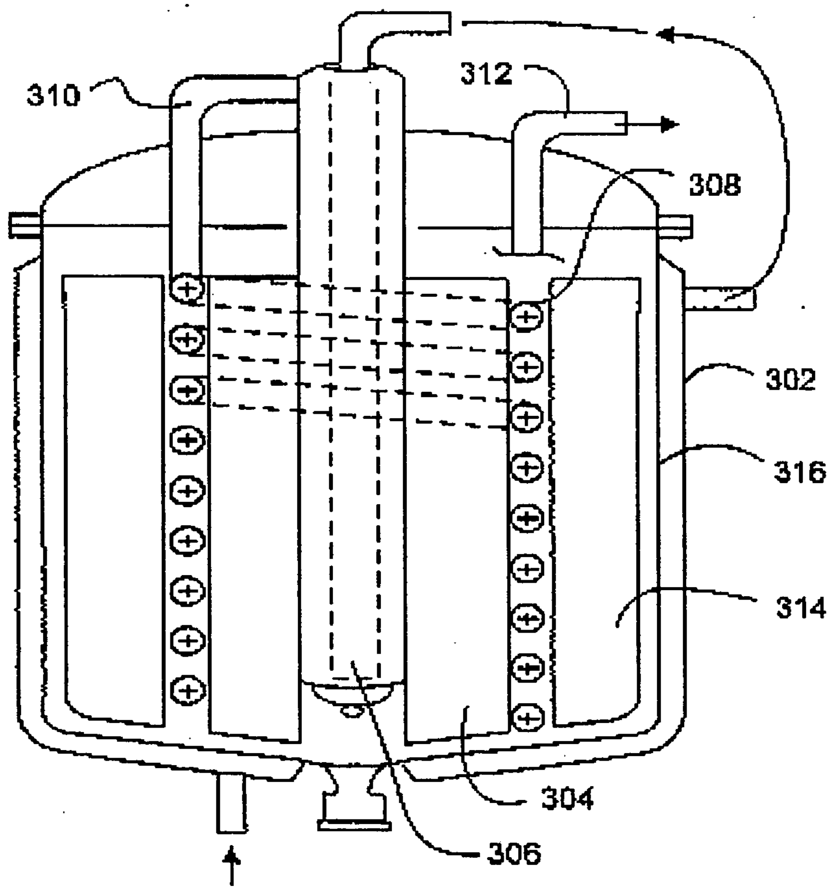


FIG. 14a

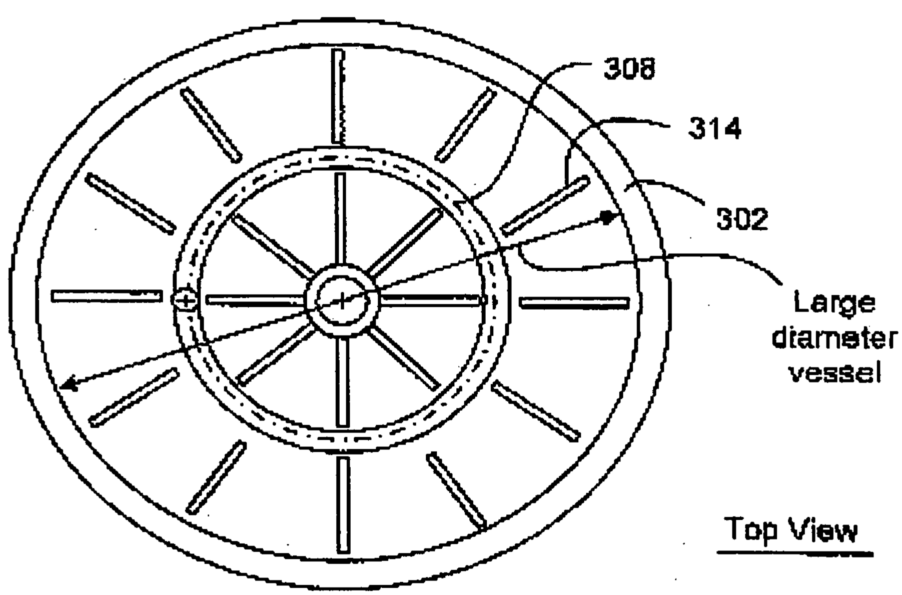


FIG. 14b

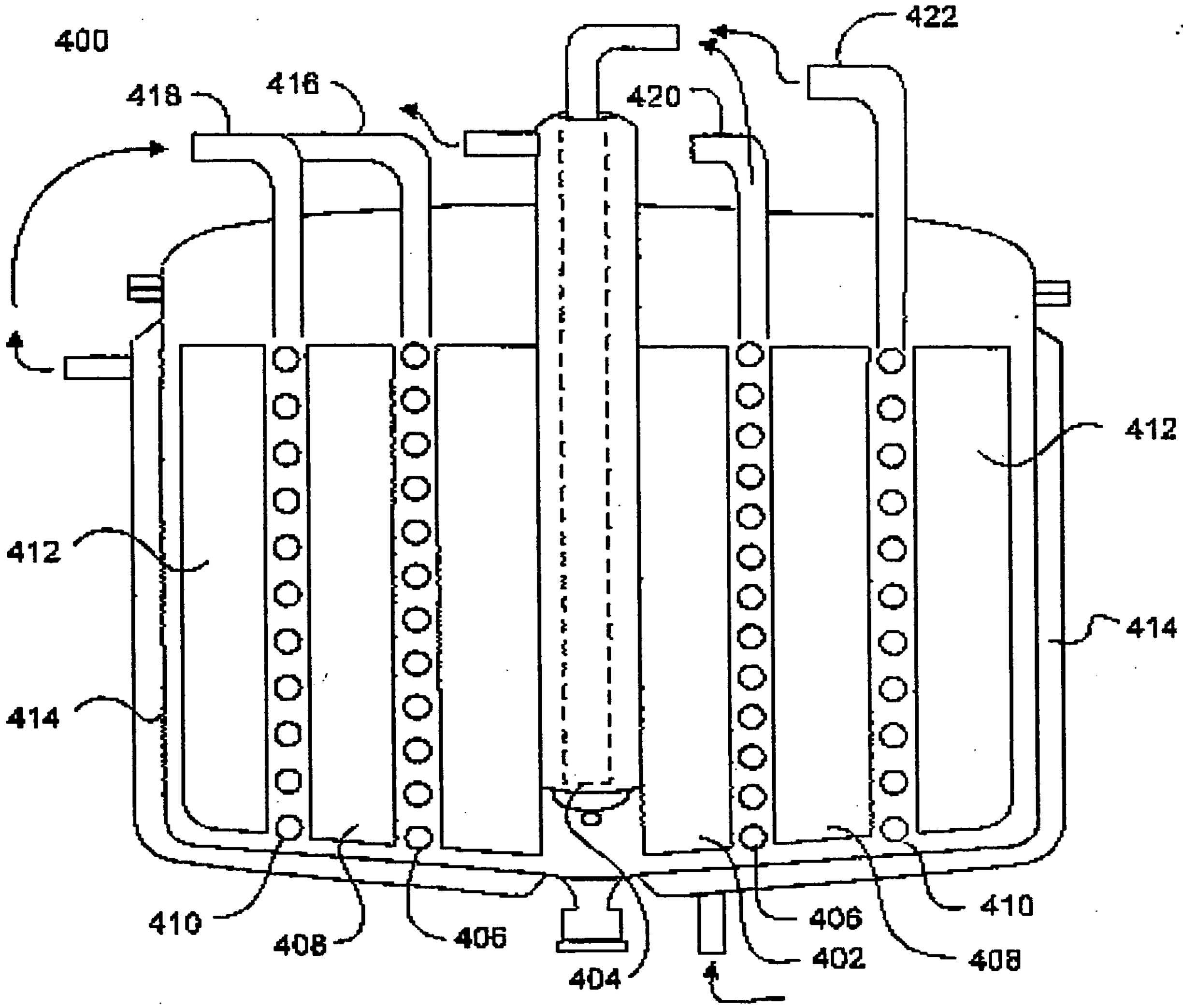


FIG. 15a

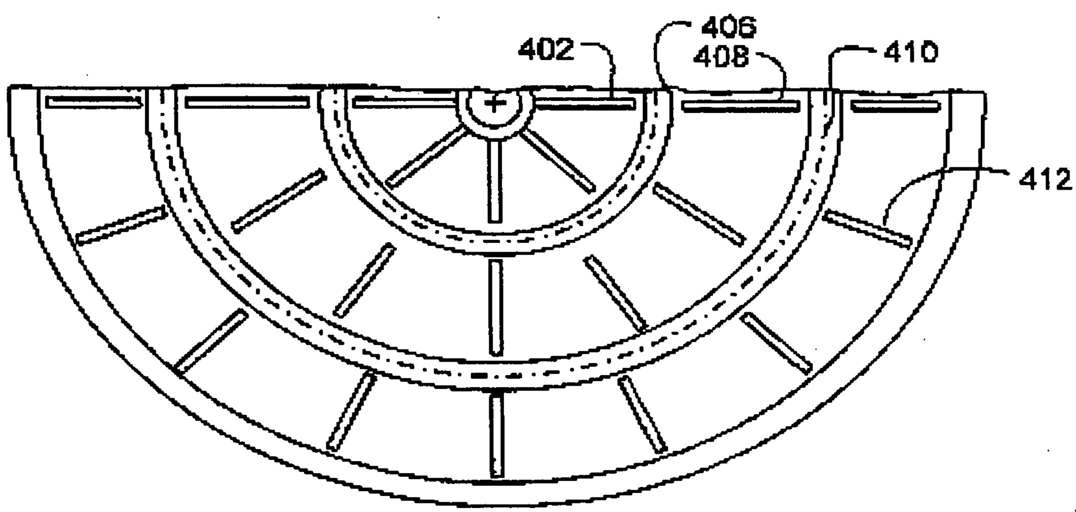


FIG. 15b

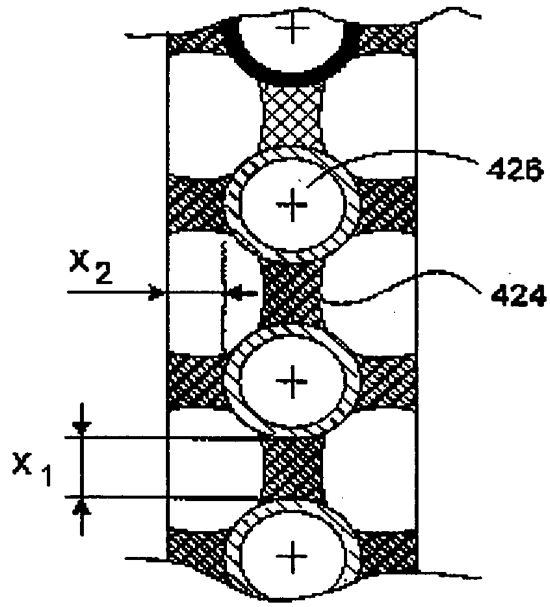


FIG. 15c

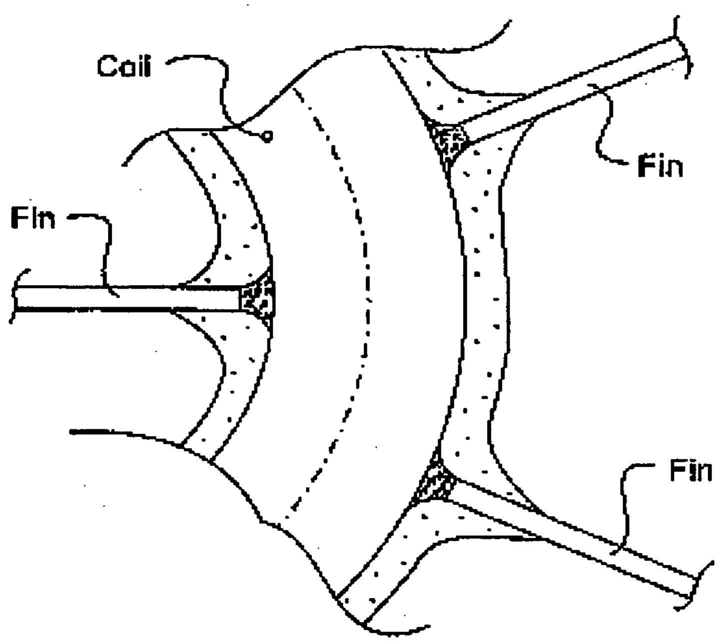


FIG. 15d

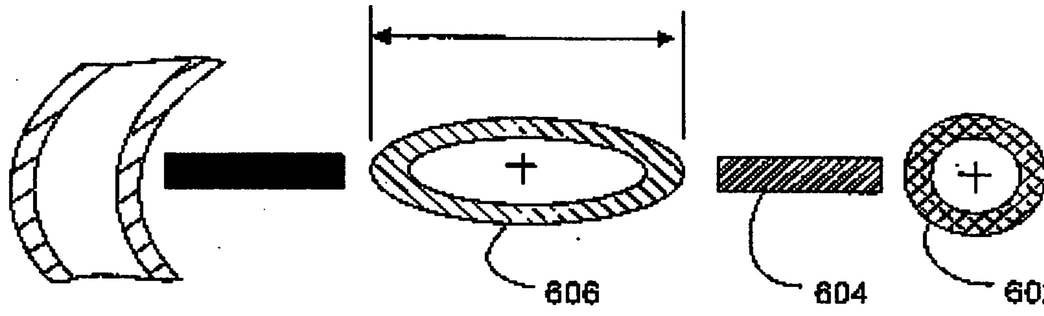


FIG.16a

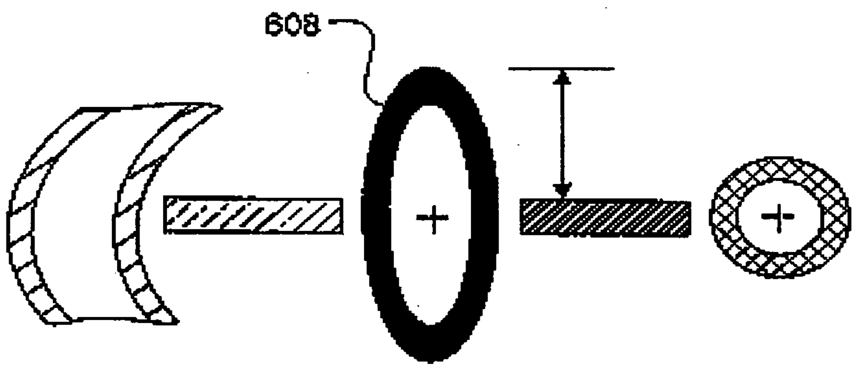


FIG.16b

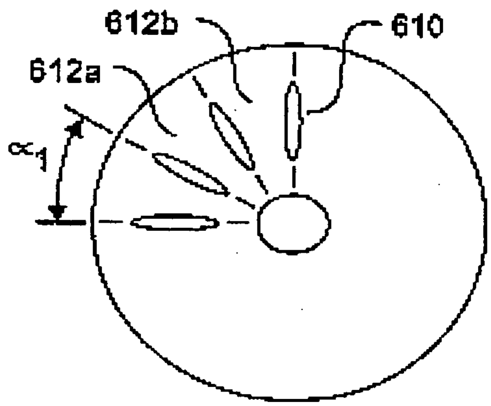


FIG. 17a

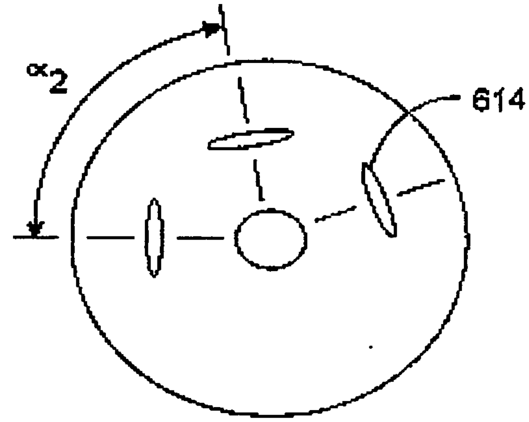


FIG. 17b

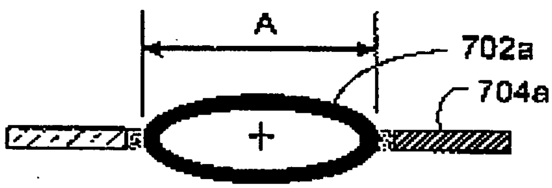


FIG. 18a

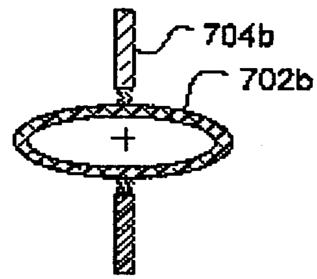


FIG. 18b

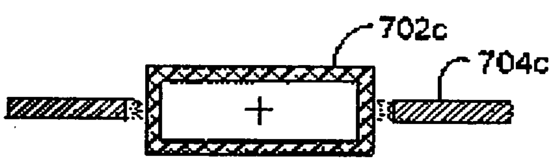


FIG. 18c

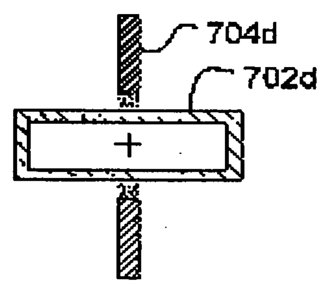


FIG. 18d

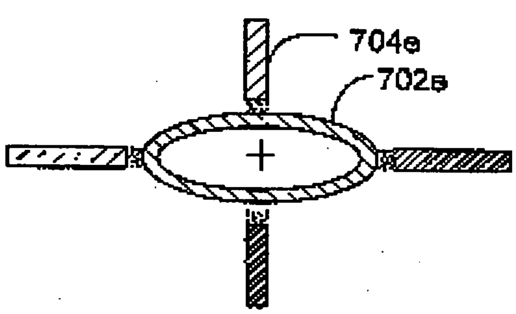


FIG. 18e

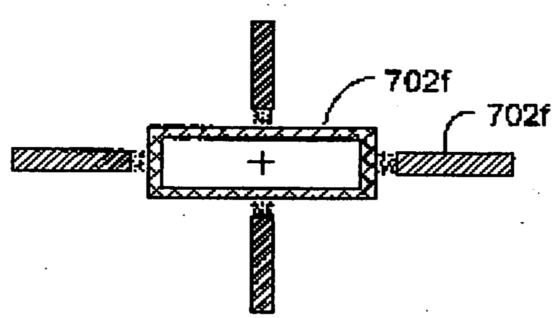


FIG. 18f

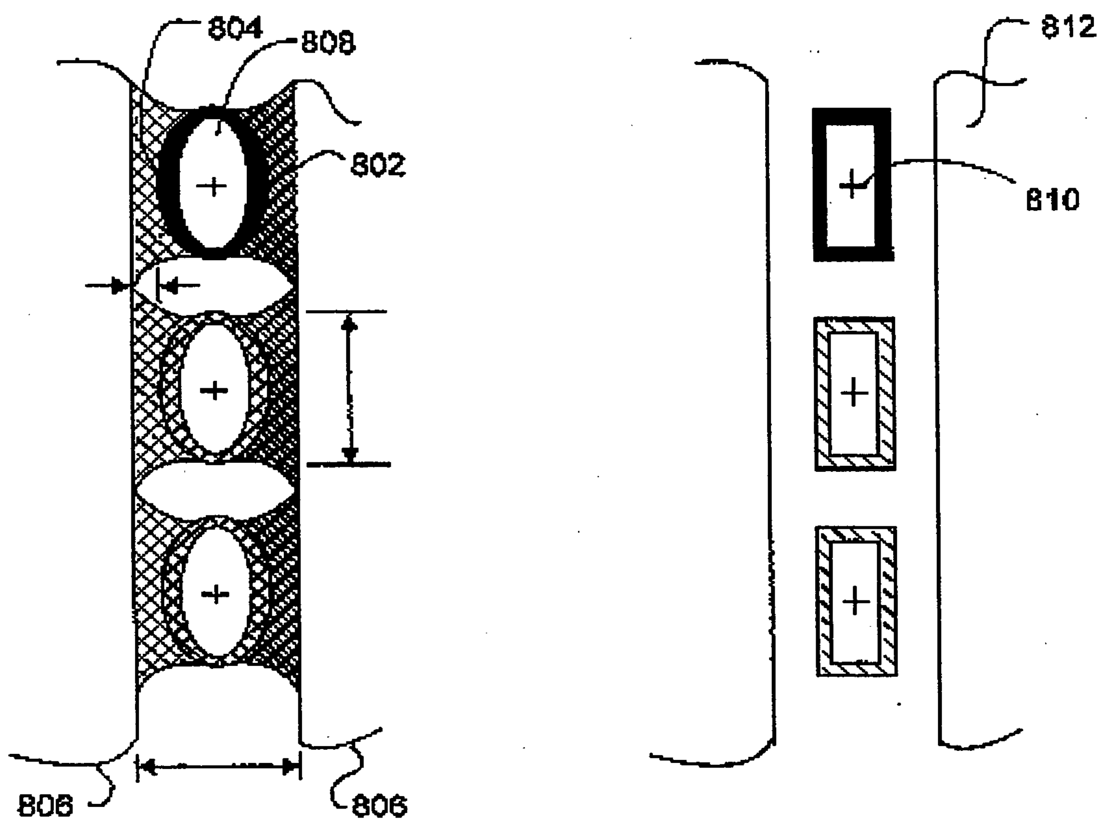


FIG. 19a FIG. 19b

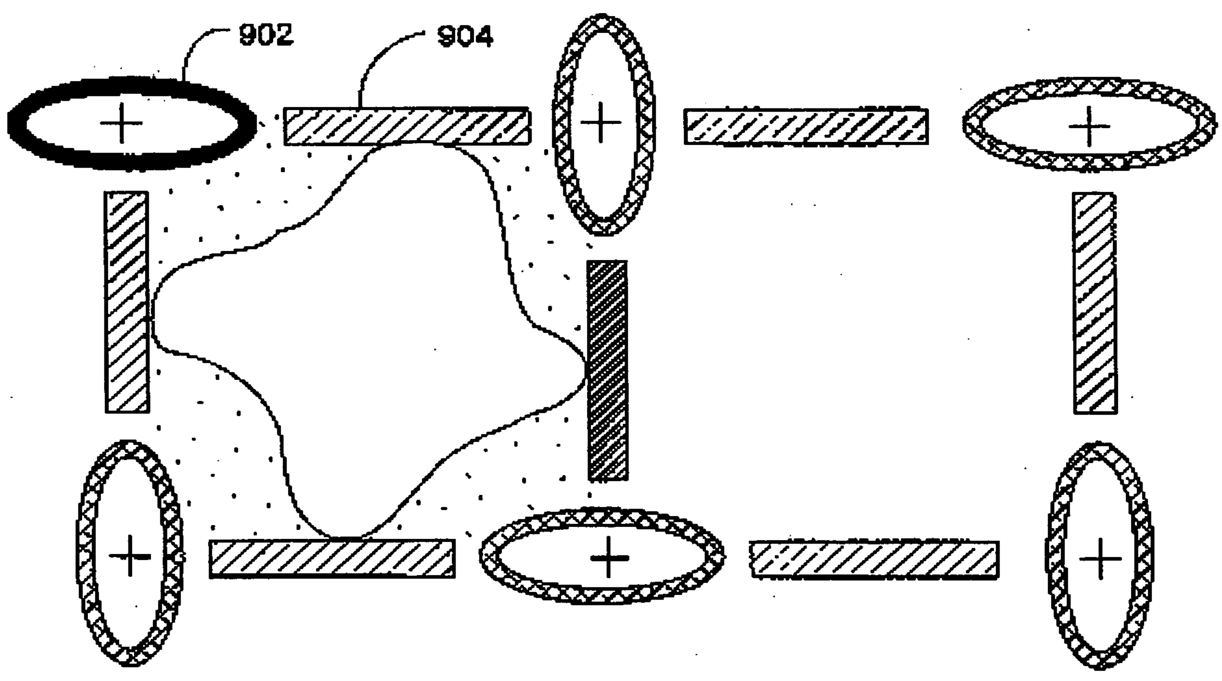


FIG. 20